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Hopeless helplines and NASty problems

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Universal board for dual audio op amps

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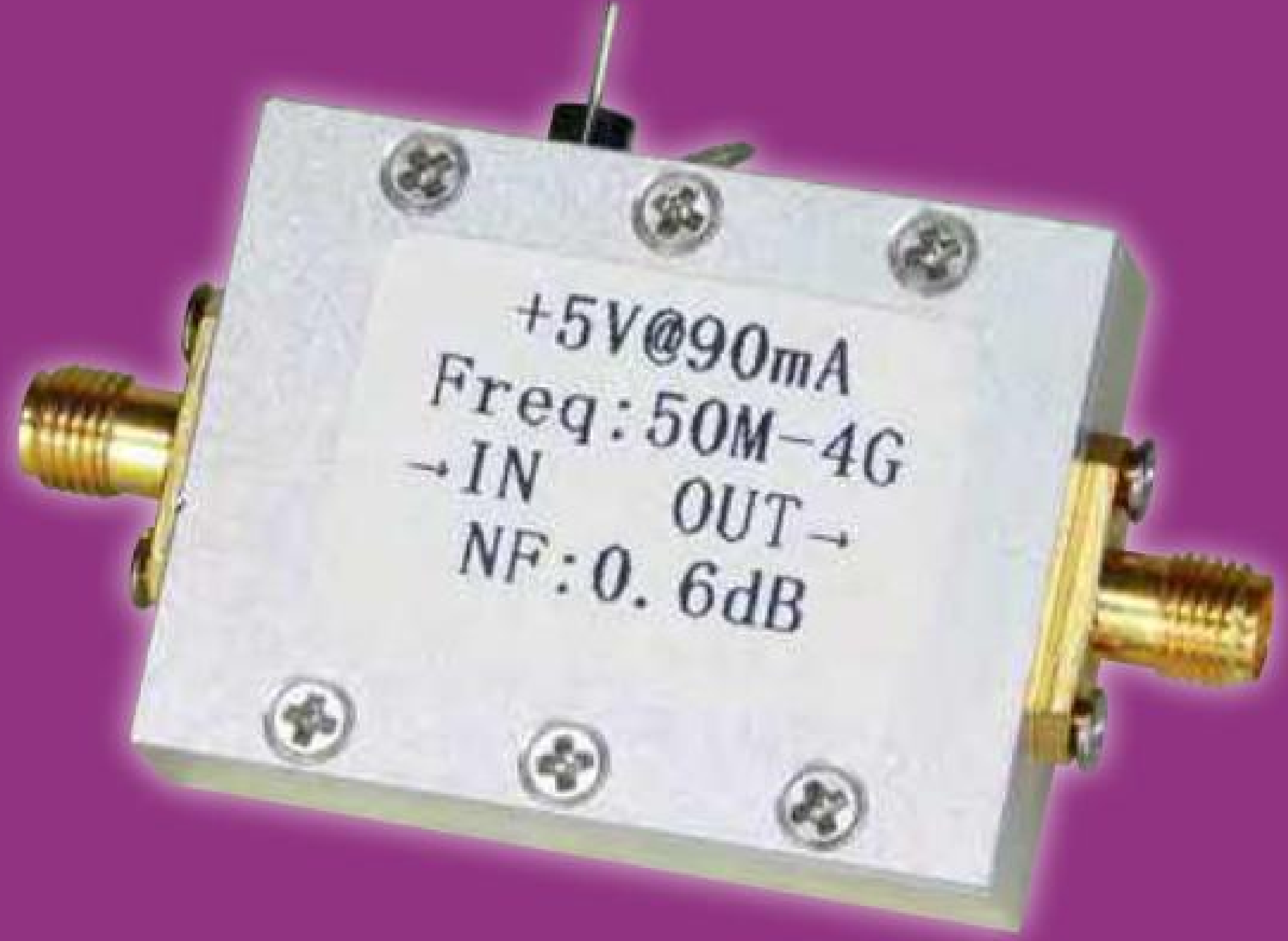

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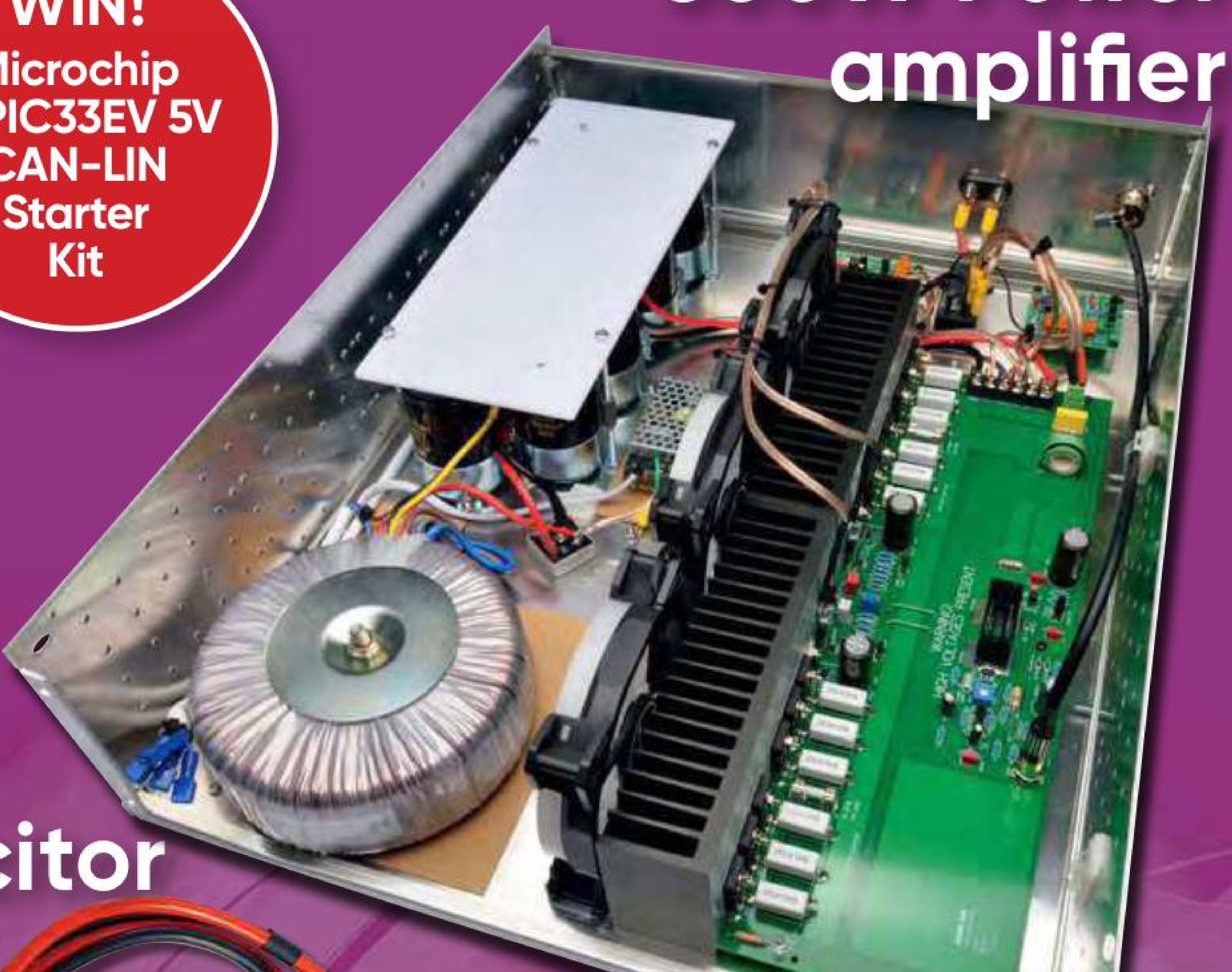
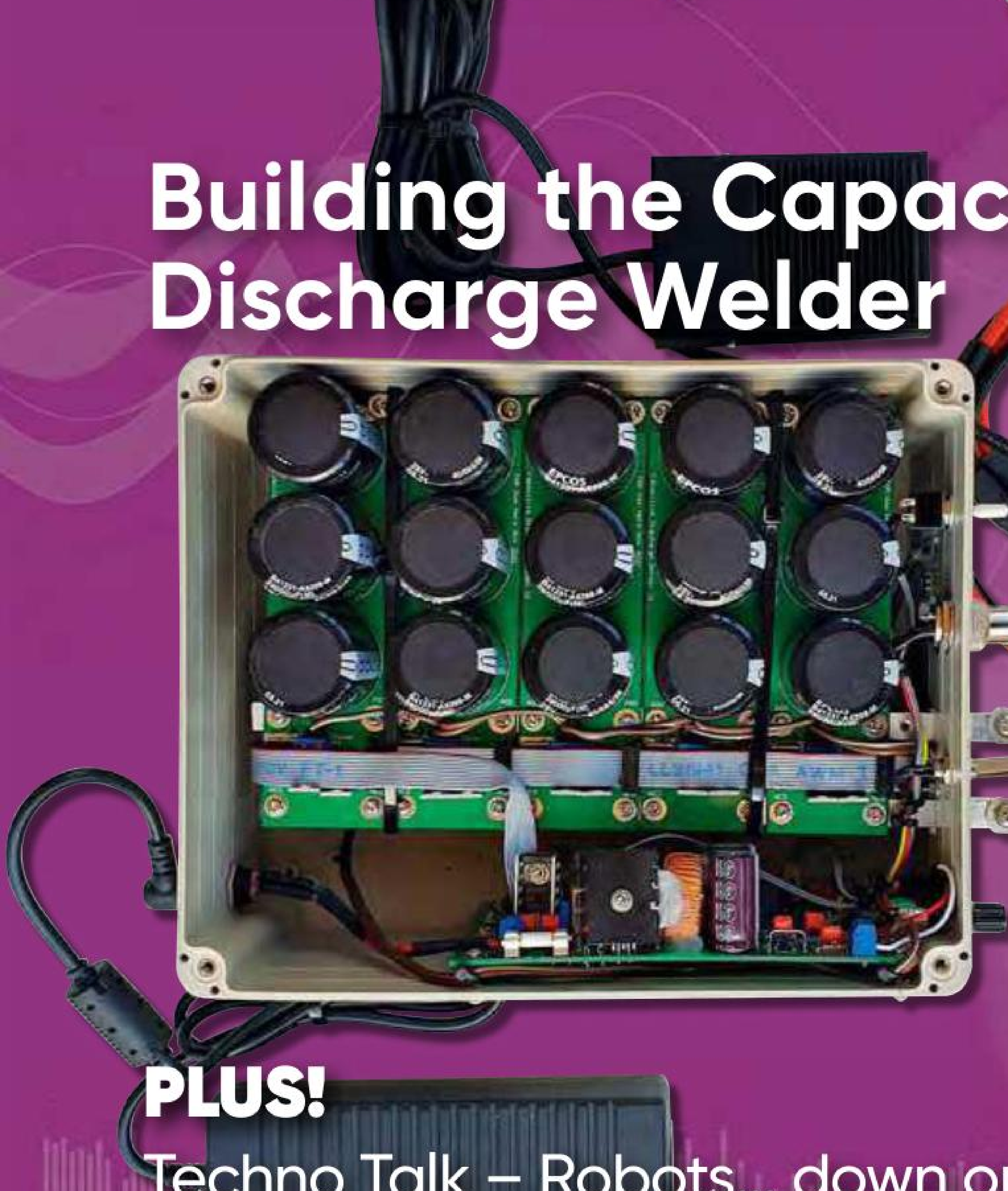
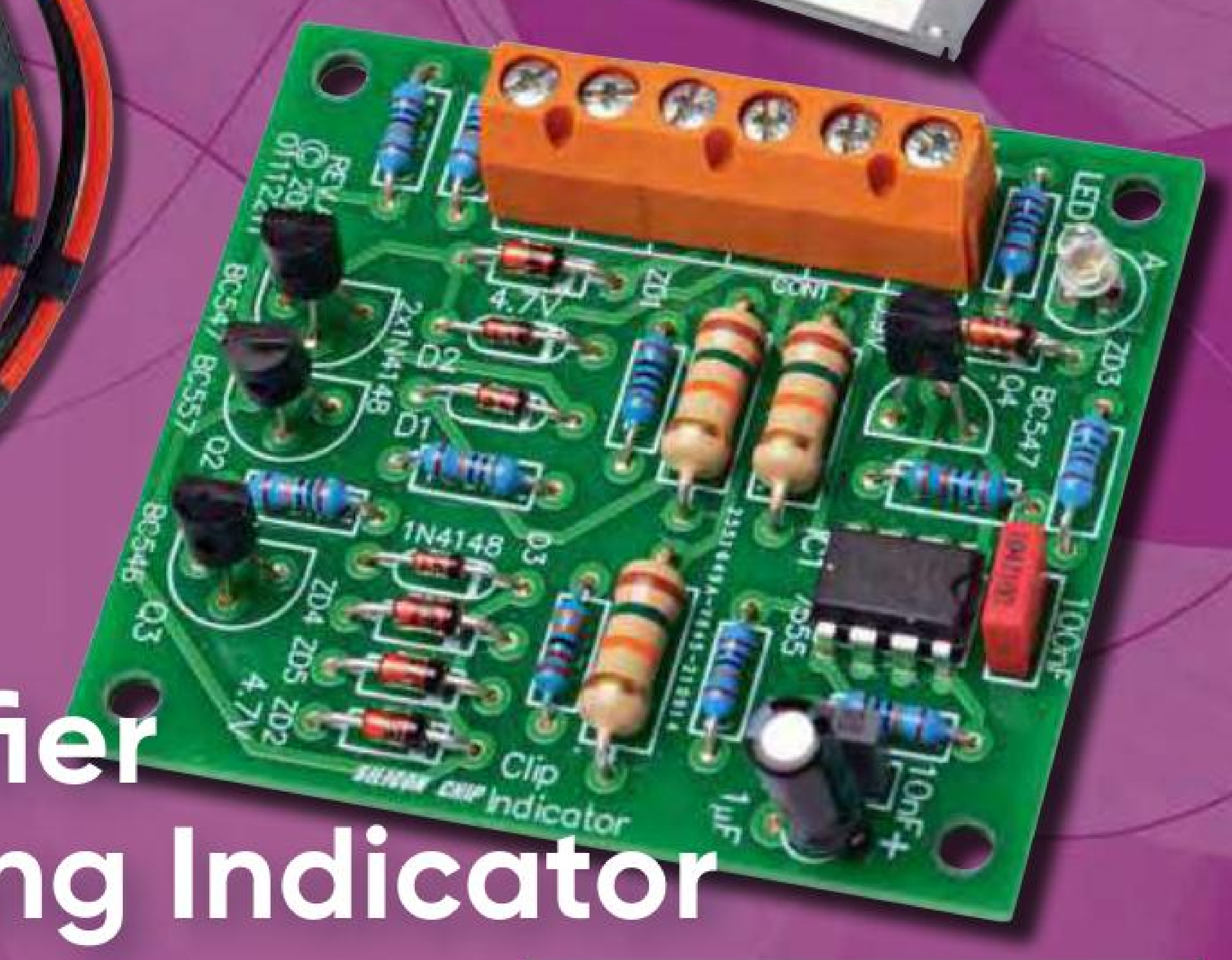
500W Power amplifier



Building the Capacitor Discharge Welder



Amplifier Clipping Indicator



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Practical
Electronics

Volume 52. No. 4
April 2023
ISSN 2632 573X

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The May 2023 issue of *Practical Electronics* will be published on Thursday, 6 April 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

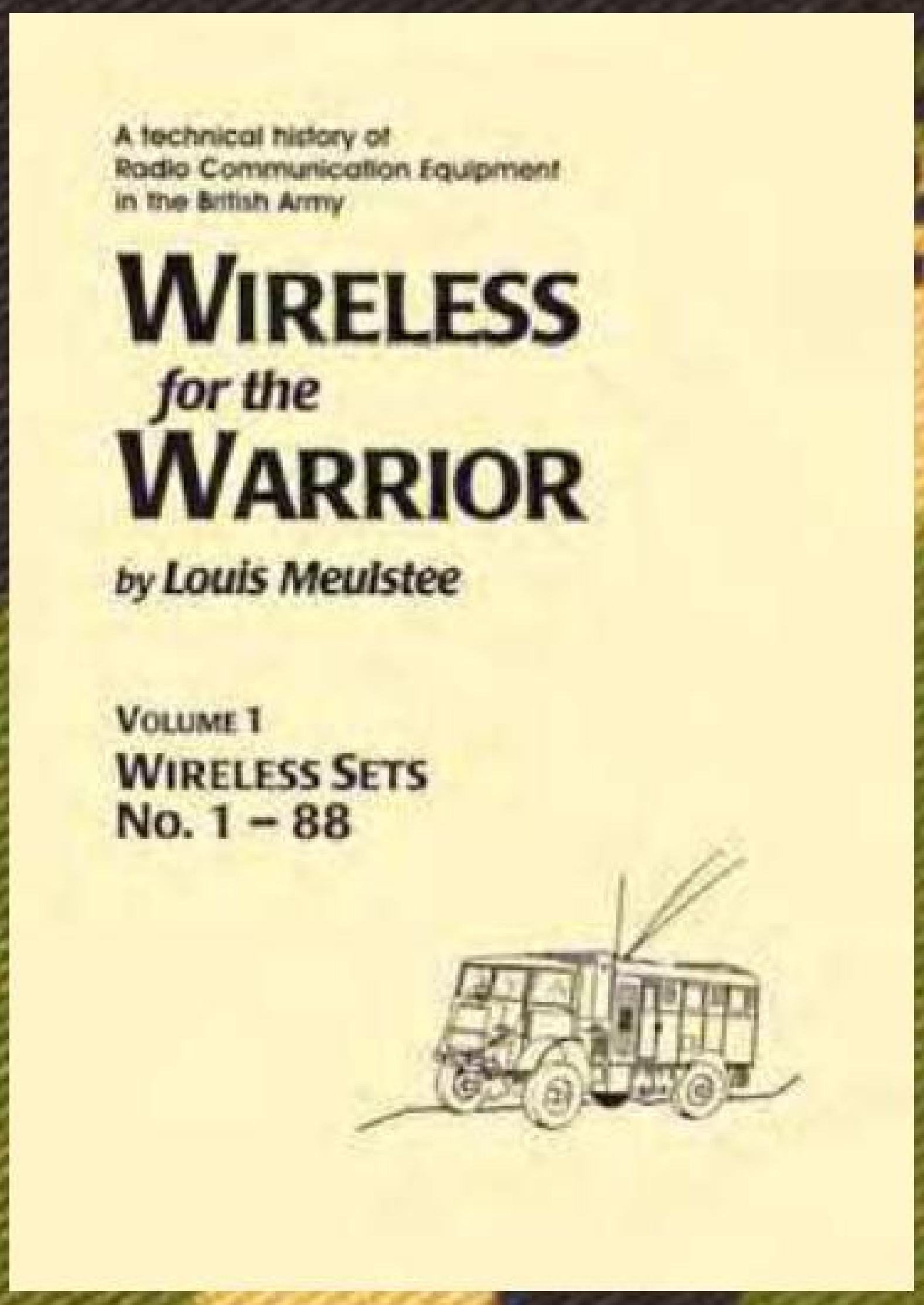
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.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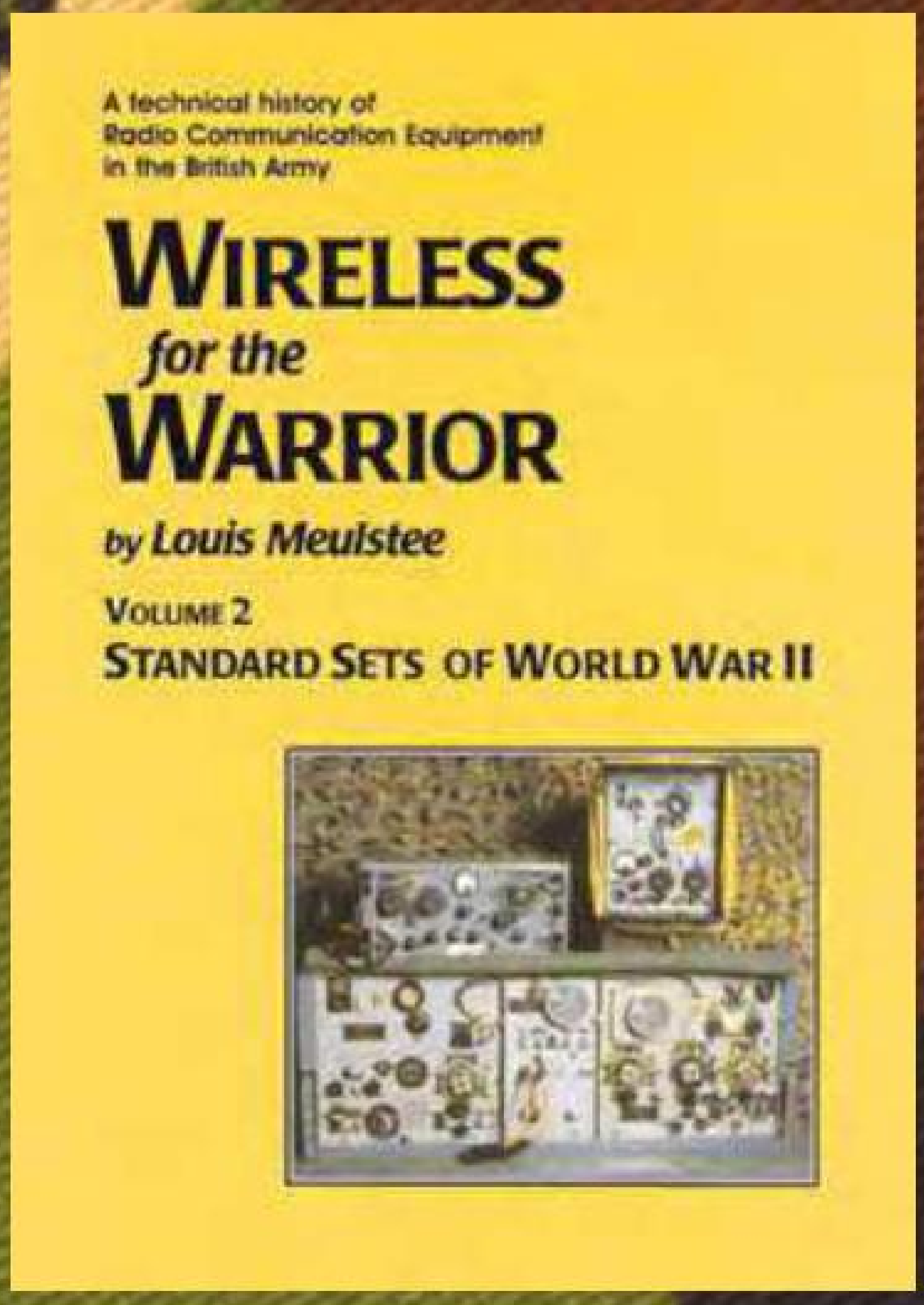
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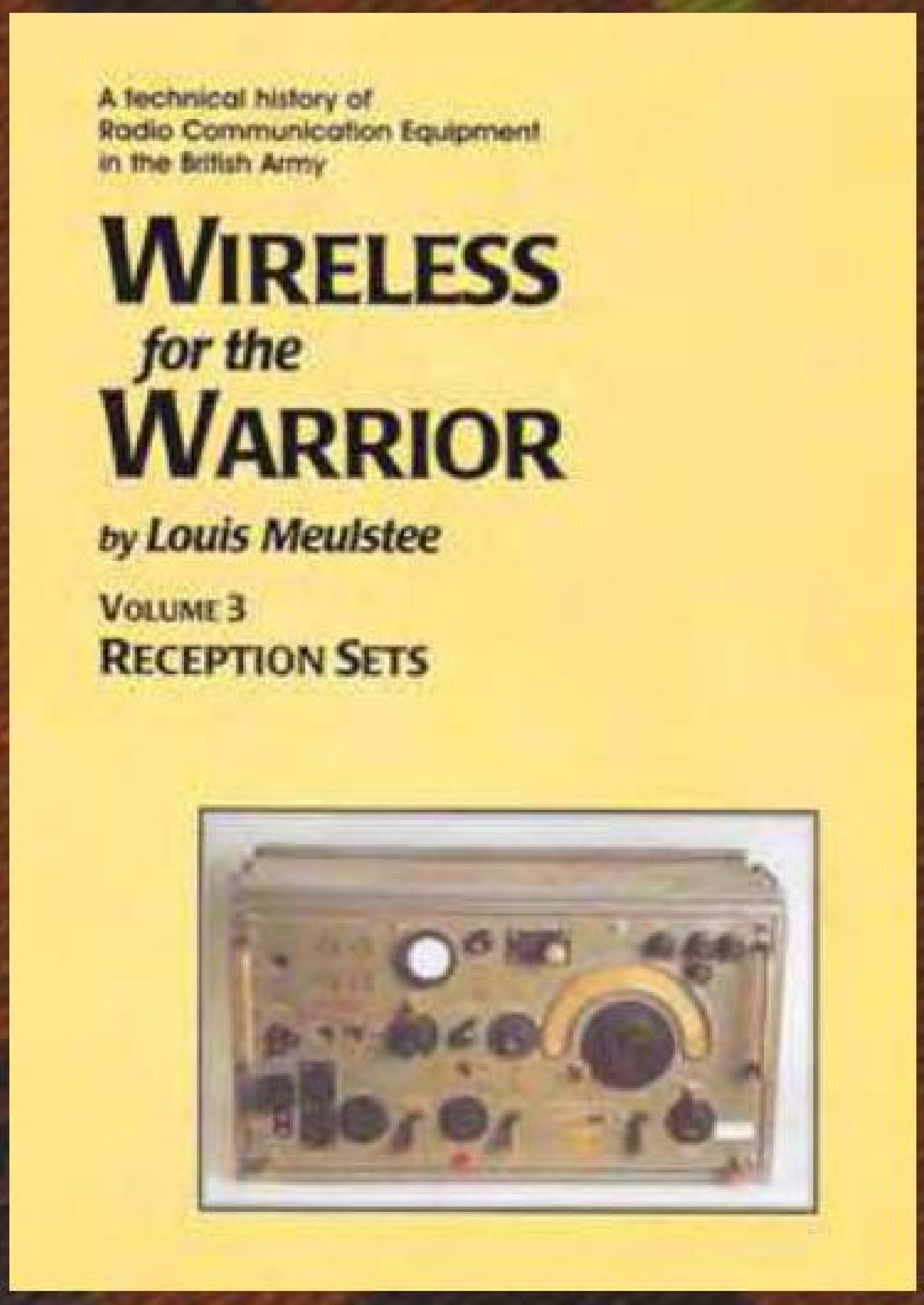
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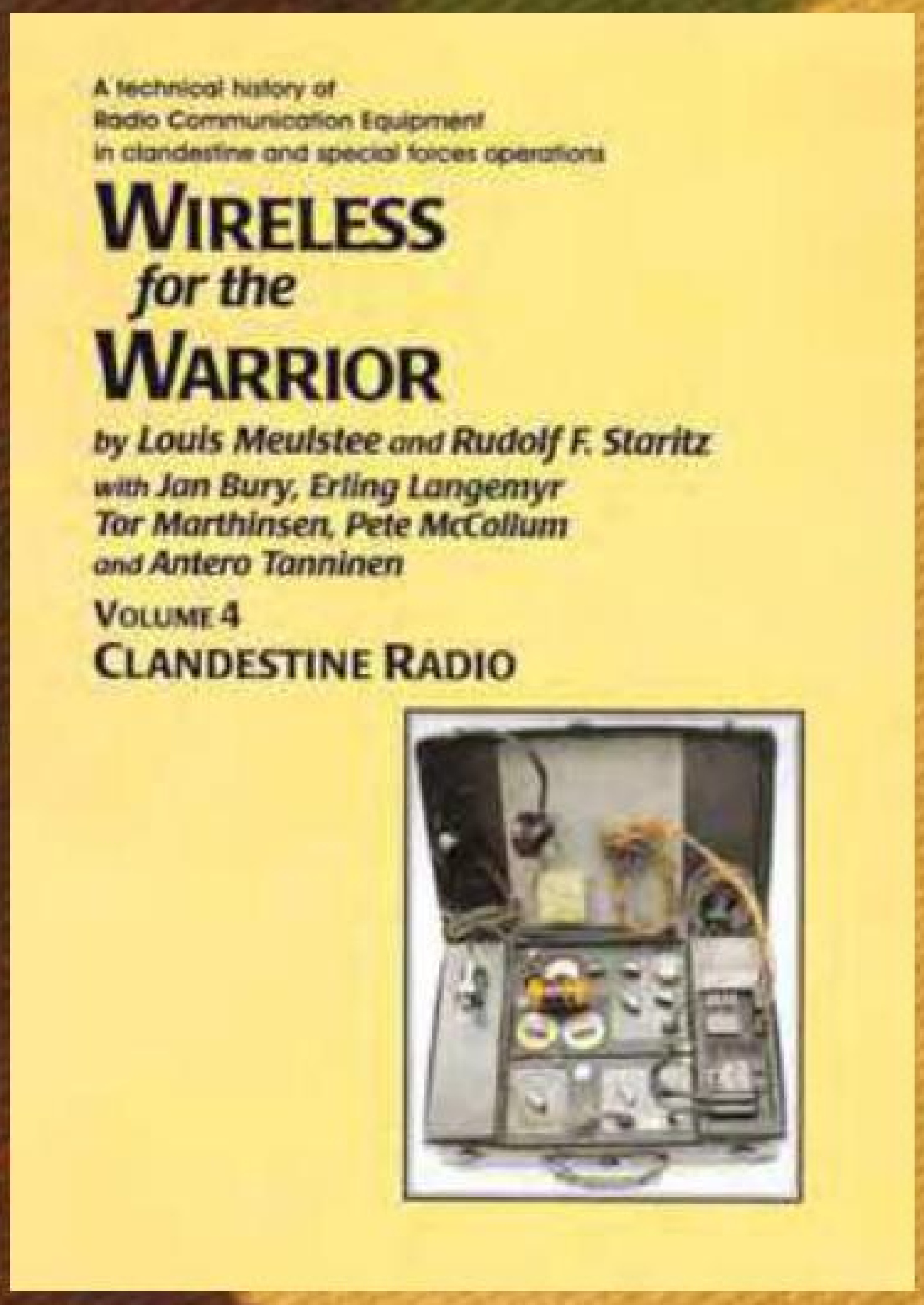
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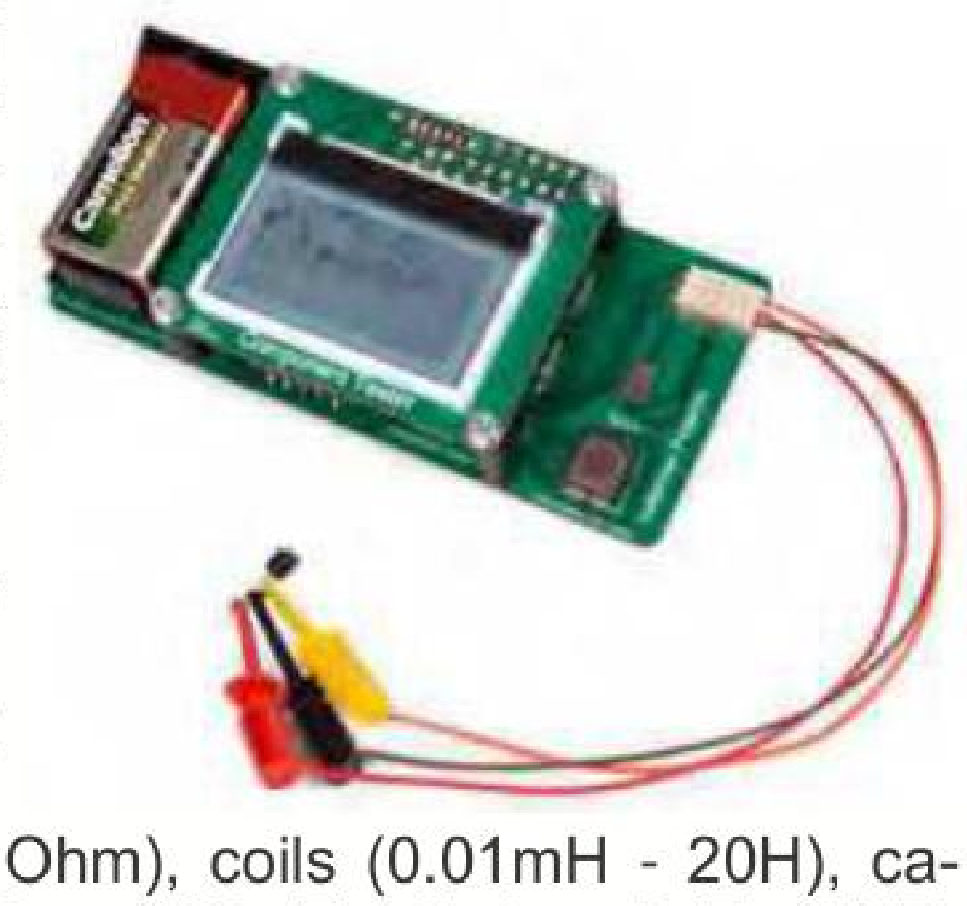

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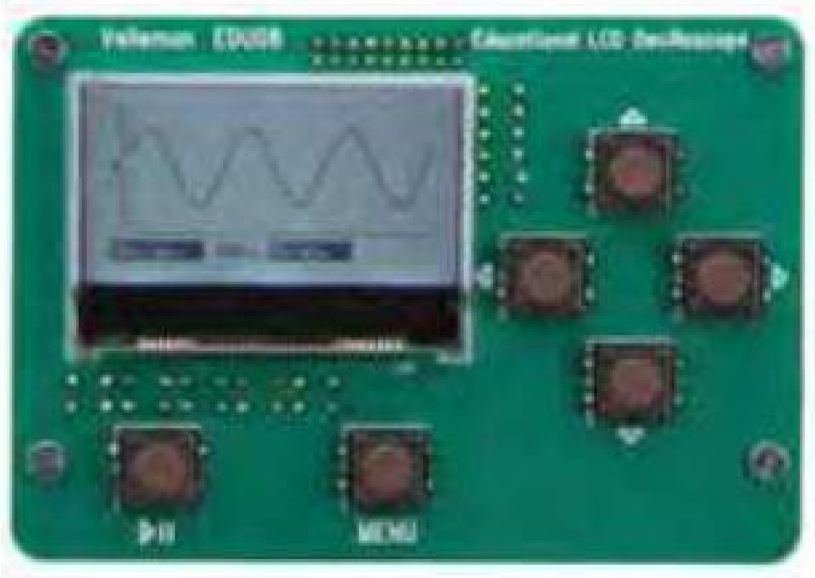

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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Power!

We have a super, packed *Practical Electronics* for you this month, especially if you like to learn about or build amplifiers. But even if that's not your primary interest we have plenty of other topics to whet your appetite for electronics.

Our two big projects are all about the control of electrical power: the conclusion of the *Capacitor Discharge Welder* and the start of a new *500W Power Amplifier*. The welder is an unusual, fascinating design – in fact, I'm not sure I've ever seen one like this before. It has a thousand and one uses for makers working with lightweight, sheet-metal designs. I'd welcome photos and reports of how you use yours – do let us know.

When it comes to headcount, there's not much doubt we produce a larger number of designs for pre-amplifiers compared to power amps. There are many more opportunities for design variation with pre-amplifiers – input choices, tone controls, remote control and so on. Plus, pre-amplifiers tend to be cheaper compared to their much larger siblings, so experimentation requires less outlay. Therefore, when a new power amplifier design does come along, we try to make it something special. This month, we present the first part of our *500W Power Amplifier* module – and yes, you read that correctly, it can output half a kilowatt! But this is no dumb, muscle-bound over-sized, clunking amp. It's a sophisticated design with a whole host of nice features from clever cooling fan control to accurate clipping detection. As with so many big projects these days, it does come with its own set of component sourcing challenges, but we have made an agreement with our partner magazine *Silicon Chip* to provide a kit of all the hard-to-find parts.

And more amps…

Following on from the popularity of the *Single Op Amp Universal Board* in the December-January issues, Jake Rothman has produced a *Dual Op Amp* version. It's a really useful design and development tool for audio and instrumentation tinkerers.

Maximum Max

In last month's editorial we bade farewell to *Techno Talk's* Mark Nelson, and welcomed Clive 'Max' Maxfield to the column. Max has hit the ground running and I thoroughly enjoyed his first piece. That's not Max's only contribution this month, he's up to *Part 4* of his must-read *Arduino Bootcamp*. If you've ever wondered why the Arduino has such a strong following but felt that digital control was perhaps not for you, then think again and read Max's thoroughly engaging pieces.

Matt Pulzer
Publisher

AI, Robots, Horticulture and Agriculture

Techno Talk

Max the Magnificent

Can you imagine visiting a farm and seeing autonomous tractors ploughing the fields while AI-powered drones zip through the sky detecting and addressing problems. Later, in a greenhouse, you find robots planting vegetables and picking fruits. Far future? It's already yesterday's news!

I've been reading science fiction ever since I was a young sprog. It's amazing to think how many of the things that once seemed to be the far-future ramblings of deranged minds are now part of our everyday lives. I'm thinking of robots, artificial intelligence (AI), and AI-powered robots in horticultural and agricultural settings.

When did people start seriously thinking about AI? We've all heard about Charles Babbage and his work on a mechanical computer called the Analytical Steam Engine circa the 1840s. We're also familiar with his assistant, Ada Lovelace, who was the daughter of Lord Byron. Babbage thought of his invention only in terms of performing mathematical calculations. Lady Ada, by comparison, realised that the data manipulated by computers was not obliged to represent only numerical values, but could instead be employed to represent more abstract symbols like musical notes. In her writings, Ada mused that future incarnations of the Analytical Engine, 'might compose elaborate and scientific pieces of music of any degree of complexity or extent.'

Not my first rodeo

This is not my first experience with AI. Things called 'expert systems' originated in the 1970s and proliferated in the 1980s. These systems embodied the first serious stab at what we think of as AI today. Unlike today's artificial neural networks (ANNs), however, expert systems were designed to solve complex problems by 'reasoning' through bodies of knowledge mainly using if–then rules.

By the 1990s, the marketing weenies had climbed on the AI bandwagon and were stamping 'Powered by AI' labels on anything that moved, much like their counterparts today enthusiastically proclaim products that have never seen a hint of a sniff of a whiff of gluten as being 'Gluten Free!' As a result, by the end of the 1990s, the word 'AI' had started to leave a bad taste in everyone's mouths.

To be honest, I'd forgotten all about AI until sometime around the early 2010s when it suddenly re-emerged on the scene with a metaphorical fanfare of sarrusophones. Now, AI is everywhere, powering everything from chatbots to drones to robots.

But who can replace a man?

One short story I read when I was a youngster was, *But Who Can Replace a Man?* Written by Brian Aldiss, this post-apocalyptic tale involved a group of robots on a farm. They were complaining that they couldn't do their work because no orders were coming from the city.

Based on rumours they'd heard about humans fighting each other to extinction, the robots decided to go to the city and take over themselves. While journeying to the city, they talk about all of the wonderful things they are going to do, until they meet a survivor. When he croaks, 'Get me food,' they all scurry to do his bidding. This classic story is available for free download: **https://bit.ly/3xAHnc4**

Autonomous tractors

Suppose we wish to spray a field of crops with pesticide. Just a couple of years ago, the way things worked would be that a human would drive a tractor pulling a sprayer whose booms extended up to 10m on either side. This would spray everything indiscriminately, whether it needed it or not. In addition to costing a lot of money, the result was vast quantities of pesticide entering the environment.

The next step was for companies like Blue River Technology to develop AI-controlled 'See and Spray' technology. In this case, the sprayer arms are equipped with cameras that look at the crops and instruct individual spray heads which plants (or parts of plants) to target. More details at: **https://bit.ly/3IAuHbx**

More recently, John Deere announced a fully autonomous tractor. Using a combination of GPS, satellite imagery, and six stereo cameras providing 360° vision, these tractors can run 24 hours a day, seven days a week, see: **https://bit.ly/3lOHNca**

Agricultural drones

Suppose you have a huge field that you've tilled and seeded and fertilised using your autonomous tractor. Now suppose that you have some sort of problem with a small portion of the crop located in the centre of the field. Perhaps an outbreak of fungus, for example.

Your first problem is detecting the outbreak as soon as it starts before it spreads. Your next problem is that your autonomous tractors (well, any tractors) are big and heavy, which means you can't use them in fields after it's been raining because they will compact and damage the soil. Even if it's not been raining, if you send a tractor in to spray the problem area, there's a good chance it will pick up fungal spores, which it will subsequently disperse as it exits your field.

One solution is to use an agricultural drone. Equipped with AI and cameras, a drone can fly over a field and detect the onset of a problem. It can then deliver whatever is required (fertiliser, insecticide…) in a highly focused and cost-effective manner. Consider the Hylio Model AG-172, for example. This beauty is the largest spray drone platform on the market! With a 150-litre capacity and up to 12m delivery width, the AG-172 can cover up to 0.4km^2/hour – see: **www.hyl.io**

Strawberry-picking robots

Recently, I've been introduced to all sorts of cool technologies, such as the EVE humanoid robot from Halodi Robotics (**www.halodi.com**). These little scamps are already being used for security and health care and supermarket applications around the world. In the case of supermarkets, for example, an EVE can wander up and down the aisles, reporting spills, detecting misplaced items and returning them to their rightful destinations, and restocking shelves as required.

Of course, robots don't have to be shaped like humans. I recently saw a video of strawberry picking robots in California. Using their cameras, these little scamps can sense texture and colour and pick just-ripened strawberries on an individual basis: **https://bit.ly/3Ia2uak**

The examples presented here are only the tip of the iceberg, and new developments are racing our way as we speak.

Win a Microchip dsPIC33EV 5V CAN-LIN Starter Kit

Practical Electronics is offering its readers the chance to win a Microchip dsPIC33EV 5V CAN-LIN Starter Kit (DM330018) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

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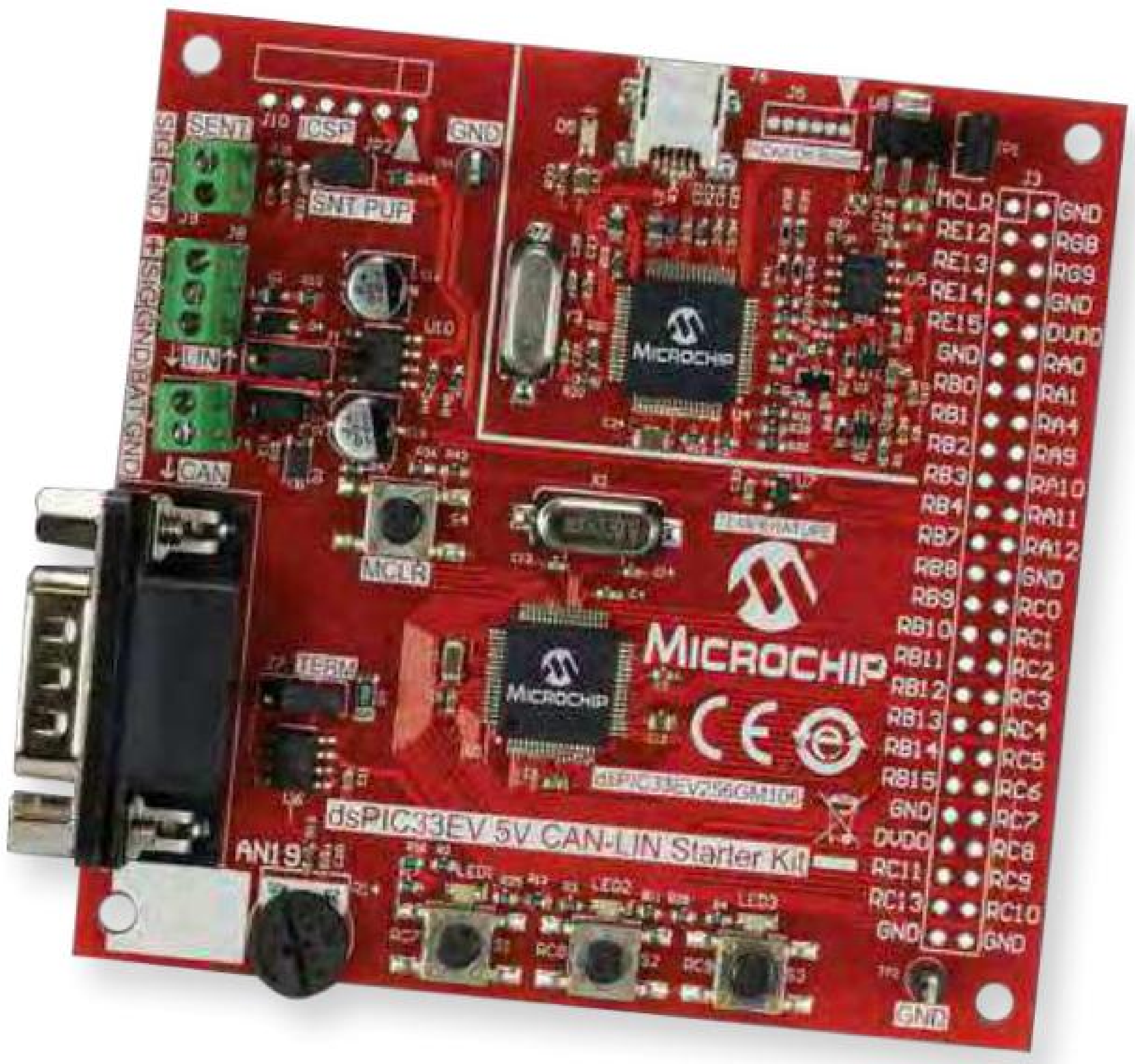

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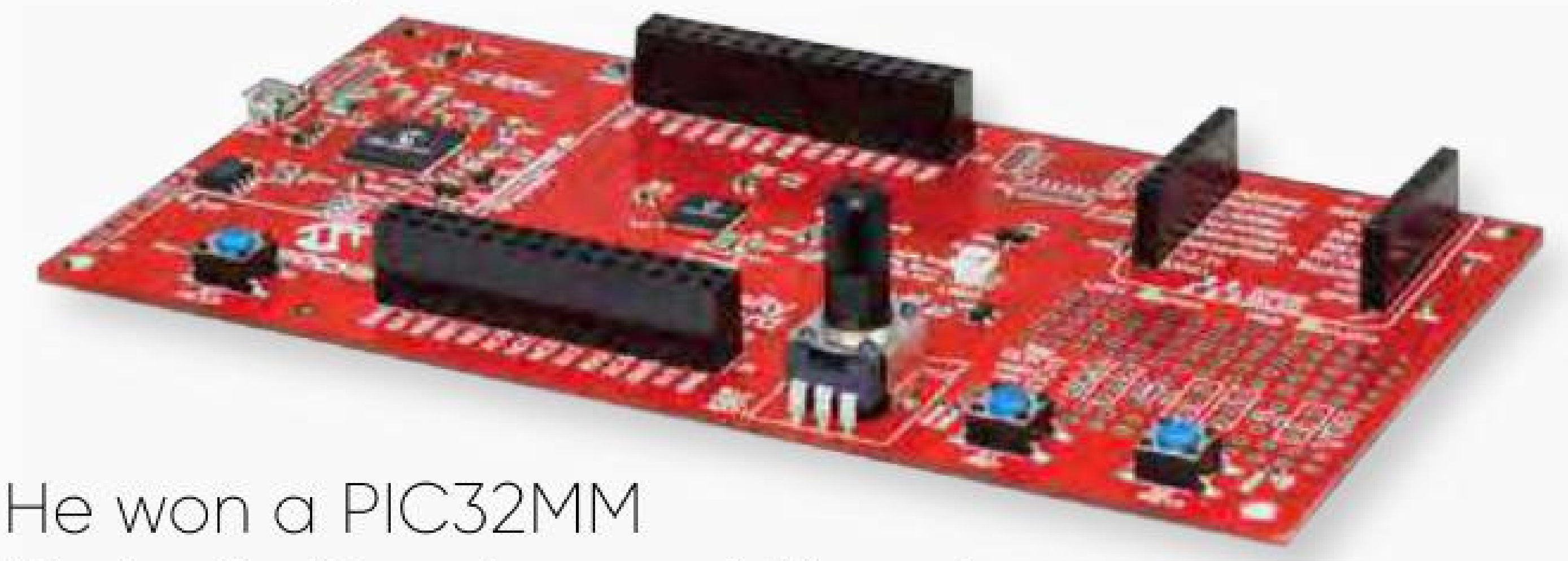
December 2022 winner

Dave Phillips



He won a PIC32MM Curiosity Development Board

The **Fox** *Report*

Barry Fox's technology column

Hopeless helplines and NASty problems

In today's endlessly 'online', never face-to-face world, too many helplines simply don't help, using faceless staff who work from a script, filibustering with instructions to try irrelevant fixes.

Sky's the limit

The last time I looked, Sky's NowTV had still not solved the problem of some programmes stopping half-way through or failing to start after the adverts which paying subscribers are forced to watch – an annoyance which brings unhappy memories of retail DVDs which could not be fast-forwarded through the jungle of trailers, adverts and promotions embedded ahead of the programme.

For many months, the adverts on Sky Now have been in audio-only. The screen only springs into life as the adverts end and the programme begins. I have greatly enjoyed not wasting my time on reporting this user-benefit fault. I'll bet many others have happily not reported it either. Sky's technical support either does not monitor its own NowTV service or is unable to fix faults. All in all, it's a win-win for paying customers.

Artificial unintelligence

If only things worked like that with other services where the customer suffers from terrible help support. In my experience, NatWest bank's Artificial Intelligence chatbot Cora is so Unintelligent that it fails to understand even the simplest customer question.

I previously reported here on a gung-ho speech made by Dan Fahy of Paramount at the annual Digital TV Group conference, ahead of the Paramount + streaming service launch. Essentially, Fahy was promising Nirvana, and in good faith I quoted him. But when I later tried the service for myself it took a time-wasting trudge of 14 emails before the Paramount Help Line admitted what it should have been able to advise immediately; although Roku streaming devices work with Paramount, the device which Roku makes for Sky is designed not to work with Paramount.

I've contacted Dan Fahy and Paramount (several times) to report what it's like for real world customers to use Fahy's help line. But no reply. With subscription service help lines the customer usually has the last word and final sanction – cancel the sub. The clear moral of any and all subscription service stories is don't subscribe to any service for a year. Instead, start off opting for a week or month, until you know it works for you. Ideally take up an offer of a free period and really test it before paying a penny.

Brainless bots

The extent to which Help and Feedback services are now under unthinking bot control is nicely evidenced by the Microsoft system used to autovet comments on this news site: **https://bit.ly/pe-ape23-msn**

I innocently tried to add a polite comment suggesting that Paramount should look at the quality of its Customer Support, and briefly noted my experience of 14 emails needed to answer a simple question. But all useful versions of the comment were repeatedly rejected with the error message 'Does not meet The Microsoft Start Community Guidelines.'

Inquisitive readers may like to experiment with their own test messages designed to discover whether it is length, content or key word that makes the Microsoft computer say, 'No'.

NASty

With expensive hardware, it may not be easy, or even possible, to get out of a deal. I'll recount one story because the fix I found for myself, with next to no useful help from the company, has much broader value.

IT company Terramaster specialises in NAS (Network Attached Storage) devices. I bought myself the solidly built, and attractively priced, two-bay F2-210, built round an ARM

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There's no such thing as a free NAS.

processor. I quickly found why it had been attractively priced; it was saddled with an out-dated Operating System (TOS Ver.4) that relied on obsolete Adobe Flash.

Terramaster said it was developing an updated, Flash-free Operating System, TOS 5. But it would work only with Terramaster's newer models such as the F2-221, which uses an Intel processor. The company, which is based in Shenzhen, Guangdong, China, and has no visible local Western contact points, offered to send me an F2-221 in return for my taking part in a Beta test on pre-release TOS 5. It sounded like a good trade, but I was soon reminded that there really is no such thing as a free lunch (or NAS).

The NAS arrived, without any HDDs, so I had to go out and buy myself two 4TB drives. Various download versions of the TOS 5 Beta followed, thick and fast, and it quickly became apparent that the way Terramaster (and probably other Chinese companies) run Beta trials is very different from the way other IT companies run them. Beta testers are guinea pigs who devote man days to installing new versions, hitting multiple problems, describing them to the Chinese developer 'Help Line', getting back multiple and often off-point suggestions on what to try, and then describing what did and didn't work, until a new version is offered and the whole time-consuming cycle starts again.

Obviously, what's needed, but is missing, is a shared database showing what issues other testers have already found. Without information sharing, everyone wastes a shedload of time on describing duplicate discoveries.

Eventually, TOS 5 limped from Beta to a series of official releases, with buggy versions quickly superseded by newer versions with fresh problems. The language barrier between English and Chinese repeatedly blocked useful help and support. I regularly took myself back to brownfield, by re-initialising the NAS with the recommended procedure – remove HDDs, run the maker's initialisation App (TNAS-PC) on a PC and replace the NAS HDDs to trigger automatic download of a bootloader App.

Obstacles abounded and with no real help from Terramaster's Help, I discovered by tedious trial and error a trick which may well be more widely useful. Here it is.

The trick

Thanks to an industry-wide move from http to https IP addressing, browsers now often refuse to load pages and throw the error message 'Not Secure'. This bedevilled the NAS set-up process. If you suffer from a similar affliction, with any procedure, try clicking on the Error display to 'Turn on Warnings'. Then try again to load the page. After several tries (how many tries seems unpredictable) the browser may throw a different error which again warns that the IP is Not Secure but now gives the option to 'Continue to Site'.

Yippee. Unfortunately, this was only the start of the obstacle course.

The HDDs for any NAS will need initialisation, which involves downloading the latest version of the NAS operating system (in this case TOS 5), formatting the HDDs, synchronising them for RAID working and creating a secure username and password with online registration.

But mysteriously, the result may be a NAS which appears to have been successfully initialised but is in fact unable to store data, even its own name and password. Repeating the initialisation, any number of times, leads to the same failure.

Terramaster Help was so totally stumped that they ended up sending me replacement hardware to try with my 4TB HDDs. The result was still the same; failure to retain data even after complete re-initialisation.

Finally – and with no meaningful help from Terramaster Help – the penny dropped. Although the NAS was checking the HDDs every time it initialised them, and then going ahead and wiping them clean, the initialisation software was sniffing the relics of the previously created NAS proprietary file system and performing only minimal HDD checks. This is comparable to the difference between a PC performing a quick, simple disc format, and slow, full formatting. The simple disc check misses any embedded HDD corruption (perhaps caused by bad shutdown or power glitches) and thus skips some set-up steps. So, any corruption buried deep inside the disc structure remains intact.

The simple (when you twig it) solution is to force the HDDs back to their 'factory fresh' state, with only unallocated space. This has to be done by physically removing the drives from the NAS, hooking them direct to a PC, by SATA lead or USB/HDD connector, and using a software tool such as Windows Disc Management App. This tool is well hidden behind: My Computer>Manage> Disc Management!

When the HDDS have been totally wiped clean, with only unallocated space, any disc initialisation process starts from greenfield and fully re-formats the discs according to its own preferred file system.

Main takeaways

The lesson to be learned here extends far beyond a troublesome Terramaster NAS. If any HDD is giving inexplicable and persistent problems, even after supposedly complete re-initialisation, try returning it to factory-fresh state with only unallocated space.

I tried sharing this fix with Terramaster and got back the 'strong' advice to replace the HDDs – which seems a very costly alternative to wiping them clean!

I suspect the language barrier is at work here. Who am I to criticise Chinese IT Help engineers for having difficulty with my English? I don't speak a word of Chinese. But, I don't try and sell IT into China.

Apart from the specific tech tip to try returning troublesome HDDs to factory fresh, unallocated state, the much broader lesson to be learned is that there are very real pitfalls in buying non-trivial IT direct from a Chinese company, with no UK subsidiary or agency to contact, and thus having to rely on Help from China.

Net Work

Alan Winstanley

This month's column brings news of the latest smart device protocol that promises 'Plug and Play' simplicity. We rediscover the British radio astronomer Frank Hyde and commemorate the end of the 'Queen of the Skies'.

The new Matter protocol for smart devices promises simple, touch-free 'plug & play' simplicity. Amazon's Alexa range has already signed up.

Ever since the Internet became the essential 'fourth utility', increasing numbers of households now use their Internet connection for managing various Internet of Things (IoT) gadgets around the home. You can control any number of IoT electrical sockets, switches, bulbs, security cameras, LED lighting strips, sensors or even a robot vacuum cleaner, pressure washer or lawnmower, all with a tap on a smartphone screen. Then of course there's turning on your electric vehicle charger remotely or downloading route maps onto the car's satnav. Plus, there are now myriad options for casting TV, music and video over the web onto your devices, which usually involves signing up to a monthly subscription or two.

Simple 'If This Then That' (IFTTT) applets enable certain basic Internet-related actions to be triggered by all kinds of events, such as notifying you when your robot lawnmower has finished, or alerting when the weather is turning for the worse, or when a certain term is 'tweeted'. More details for experimenters, together with both free and subscription-based plans are available at: **www.ifttt.com**

As regular readers know, I've been trying out some TP-Link 'Tapo' smart devices using a budget-priced Mercusys (also made by TP-Link) whole home mesh system. I found that they mostly work well enough, most of the time, but the system is not entirely trouble-free. When things go wrong (eg, a smart bulb doesn't respond), troubleshooting can be frustrating and time-consuming. Is the problem caused by the Wi-Fi home mesh hubs, the smart bulb itself, the app, the broadband connection, or (say) Amazon's cloud?

Now, as I write, one Tapo bulb (lifespan 15,000 hours) has failed after 750 hours. I've probably been unlucky, but the usual rigmarole followed: soft-resetting, hard-resetting, re-installing, re-booting, checking the firmware, trying it in another light fixture and so on – complications that a non-technical user might struggle to do. TP-Link's boilerplate support was polite and responsive, and a free replacement was offered, provided I post the faulty item back at my expense.

It really Matters

The Internet of Things has grown over the years in quite a piecemeal way, with manufacturers adopting their own protocols to suit their smart products. Some smart device standards include Zigbee and Z-Wave, but they use different frequencies and are not inter-operable.

The Zigbee protocol is a wireless device control standard that was developed at a time when Wi-Fi and the likes of Bluetooth were first taking shape. It's getting on for 20 years old and is used by Bosch and Philips, for example, but Apple (HomeKit), Samsung (ARTIK), LG (AllJoyn) and others have scrambled to jump onto the home network bandwagon, each having their proprietary protocols.

In an effort to simplify the way in which smart devices are designed, sold, set up and (at last!) work together, the Connectivity Standards Alliance (the name behind Zigbee) has now finalised a new, IP-based open standard protocol that readers will gradually start to hear about when they shop for IoT gadgetry. The new 'Matter' protocol will become the touch-free 'Plug-and-Play' standard for the smart device world, and it's intended to unify the installation and operation of Matter-compatible smart devices. It's also designed to enable manufacturers to turn around new Matter products more quickly.

It's claimed that Matter will unite IoT interoperability in the future and

Fans of IoT home, garden and office control of smart devices, gadgets and gizmos should keep an eye open for the Matter logo.

Matter-compatible smart devices will become a breeze to set up and manage. An added benefit is that Matter devices can communicate locally between themselves, instead of having to reach out to the cloud before phoning home with a response (as would, say a Tapo smart bulb controlled by an Alexa skill – which might account for some smart bulb problems that I experienced). Apart from assuring us of future compatibility, we are told there is no need to throw away old devices as 'Matter will play nicely with them'. Nice words, but time will tell.

Readers might watch out for the new Matter logo that will gradually appear on new generation IoT product spec sheets. Google, Samsung and others are very slowly rolling out updates and a handy status list of Matter compatibility is at: **https://bit.ly/pe-apr23-mtr1** (noting that mostly we see 'announcements' confirmed rather than 'ready' at the present time).

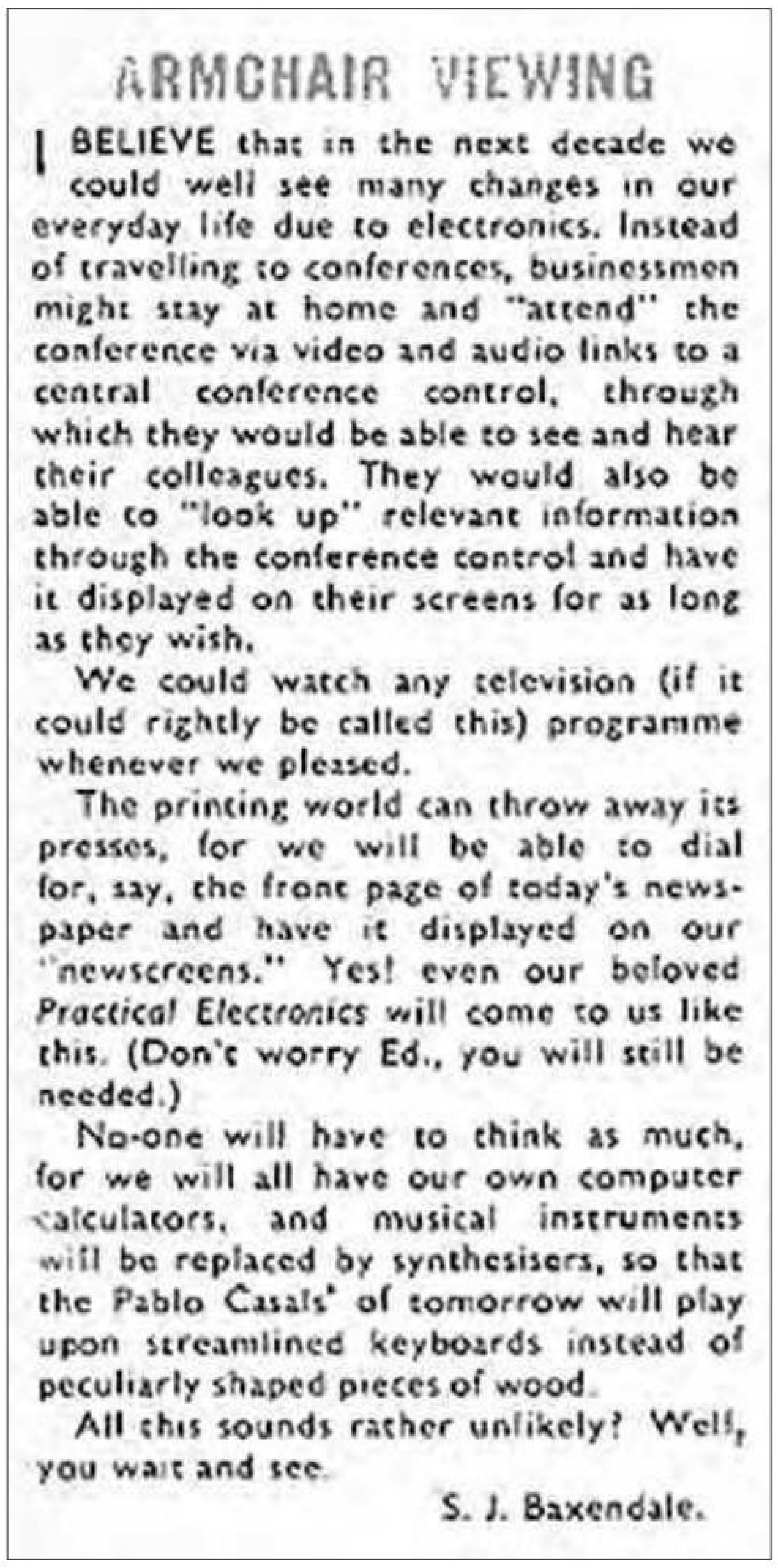
You can learn more about Matter at the CSA YouTube video at: **https://bit.ly/pe-apr23-mtr2** – commendably, it's a very smooth six-minute explanatory video that (remarkably) was filmed in a single take and without any cuts. The CSA website also has more at: **https://bit.ly/pe-apr23-mtr3**

The era of an altogether smarter home is hopefully arriving, thanks to the new Matter protocol which should finally put paid to all those compatibility, setup and installation frustrations.

Watch this Space

Periodically, I find myself sifting through my old electronics magazines in search of facts or some historical information. Sometimes my hours-long searches are fruitless, but nevertheless I come away having been reminded of how things were, many decades ago. I never cease to be amazed at the foresight that some of our readers (and writers) showed when they predicted what the future would likely bring: in the January 1975 issue of *Practical Electronics*, for example, the advent of 'working from home' and the world-wide web, as well as the use of smart meters and RFID tags, were correctly forecast, if slightly ahead of their time!

As some long-time readers of early *Practical Electronics* magazines may know, *PE* originally had a dedicated column called *Spacewatch* which brought the latest news of space exploration, radio astronomy, the moonshot and the ambitions of various space satellite programmes. Recall how Russia managed in 1957 to beat the US into space by launching Sputnik, an 'alarming' event that hastened the creation of the Advanced Research Projects Agency (ARPA) – see **https://bit.ly/pe-apr23-darpa** – and accelerated the need to build a 'self-healing' robust packet network that would form the basis of the Internet itself.



ARMCHAIR VIEWING

I BELIEVE that in the next decade we could well see many changes in our everyday life due to electronics. Instead of travelling to conferences, businessmen might stay at home and "attend" the conference via video and audio links to a central conference control, through which they would be able to see and hear their colleagues. They would also be able to "look up" relevant information through the conference control and have it displayed on their screens for as long as they wish.

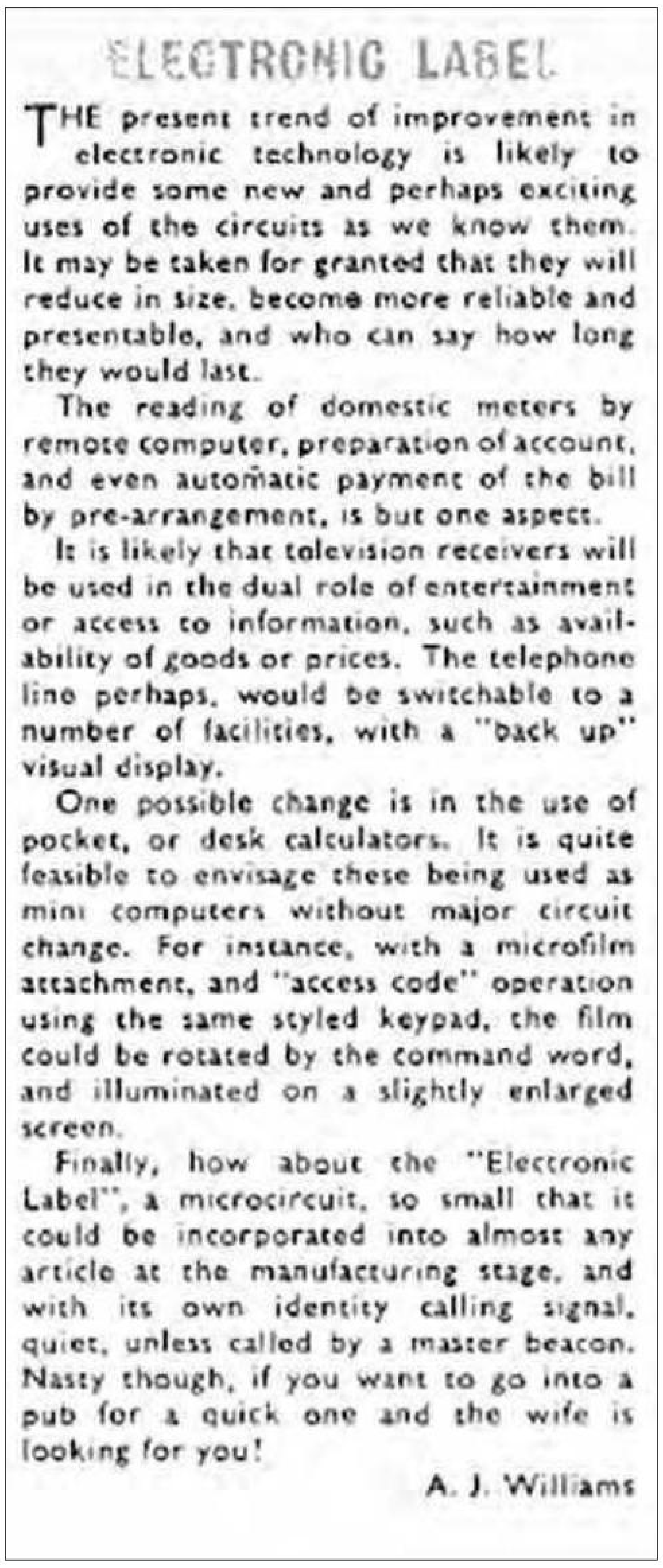
We could watch any television (if it could rightly be called this) programme whenever we pleased.

The printing world can throw away its presses, for we will be able to dial for, say, the front page of today's newspaper and have it displayed on our "newscreens." Yes! even our beloved *Practical Electronics* will come to us like this. (Don't worry Ed., you will still be needed.)

No-one will have to think as much, for we will all have our own computer calculators, and musical instruments will be replaced by synthesisers, so that the Pablo Casals' of tomorrow will play upon streamlined keyboards instead of peculiarly shaped pieces of wood.

All this sounds rather unlikely? Well, you wait and see.

S. J. Baxendale.



ELECTRONIC LABEL

THE present trend of improvement in electronic technology is likely to provide some new and perhaps exciting uses of the circuits as we know them. It may be taken for granted that they will reduce in size, become more reliable and presentable, and who can say how long they would last.

The reading of domestic meters by remote computer, preparation of account, and even automatic payment of the bill by pre-arrangement, is but one aspect.

It is likely that television receivers will be used in the dual role of entertainment or access to information, such as availability of goods or prices. The telephone line perhaps, would be switchable to a number of facilities, with a "back up" visual display.

One possible change is in the use of pocket, or desk calculators. It is quite feasible to envisage these being used as mini computers without major circuit change. For instance, with a microfilm attachment, and "access code" operation using the same styled keypad, the film could be rotated by the command word, and illuminated on a slightly enlarged screen.

Finally, how about the "Electronic Label", a microcircuit, so small that it could be incorporated into almost any article at the manufacturing stage, and with its own identity calling signal, quiet, unless called by a master beacon. Nasty though, if you want to go into a pub for a quick one and the wife is looking for you!

A. J. Williams

In 1975, *PE* reader SJ Baxendale eerily foresaw working from home, video conferencing, the world-wide web and on-demand TV, while AJ Williams forecast the use of smart meters and RFID tags!

Net Work's interest in space programmes is mainly focussed on the idea of Internet connectivity beaming down from a growing constellation of satellites stationed in LEO (low-earth orbit). The main contender is of course SpaceX, whose Starlink service now hosts some 3,300 satellites, inter-communicating using lasers. My computer/IT colleague has been impressed with the ease of setting up Starlink terminals for UK customers, but the running costs will deter mainstream users. You can sign up for satellite-based Internet connectivity at: **starlink.com**

A glance through our 1960s archives revealed plenty for *Spacewatch* columnist Frank Wilsenham Hyde to write about in his occasional column that first appeared in 1967. That was at a time when NASA and Russia were living through their share of triumphs and tragedies while competing to develop space exploration programmes and technologies, and when the attraction of putting man on the Moon beckoned brightly.

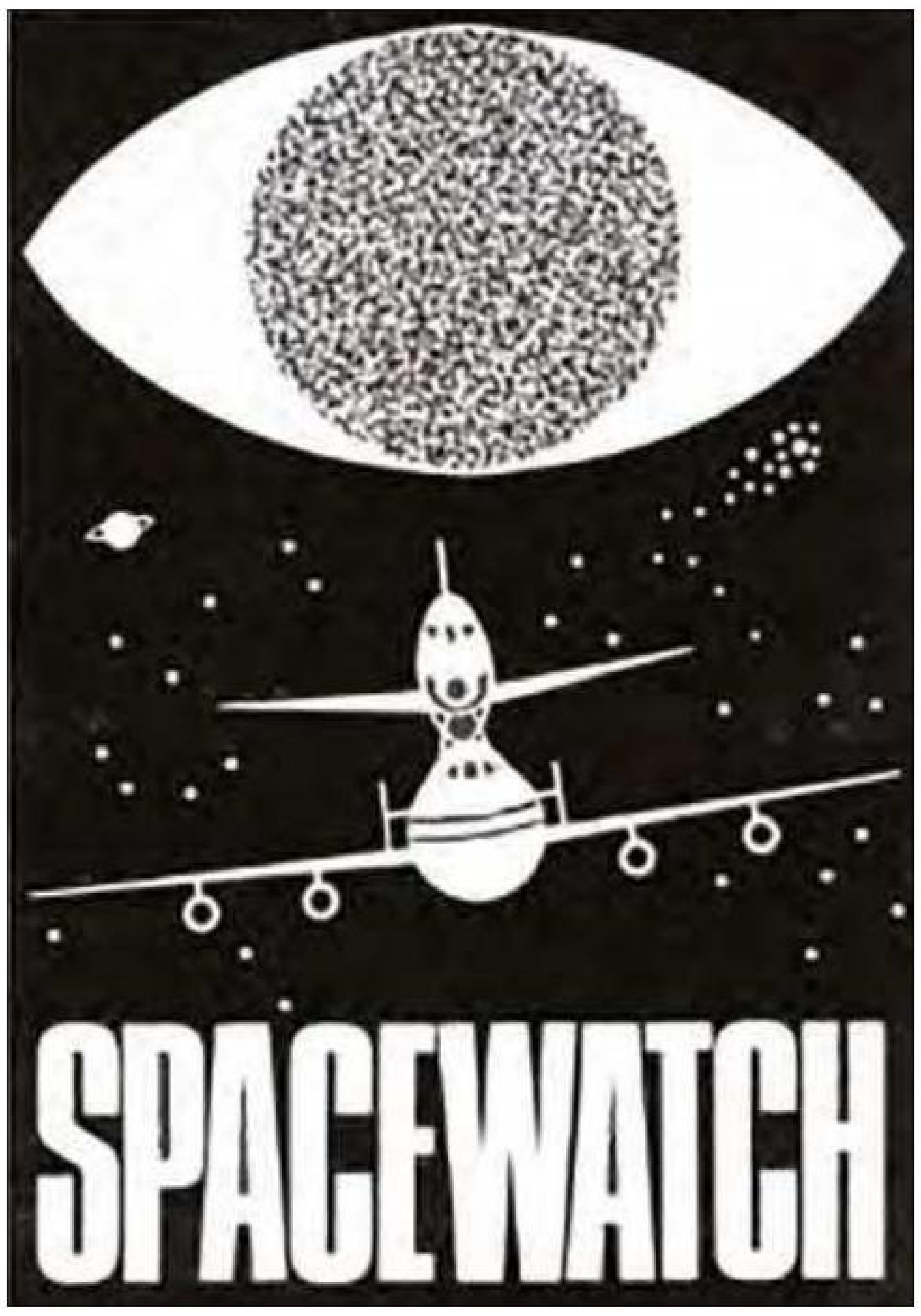
I was not yet a teenager when *Spacewatch* went monthly in *Practical Electronics* from the April 1969 issue, following the remarkably successful Apollo 8 manned lunar orbit mission, see: **https://bit.ly/pe-apr23-nasa1**

NASA astronauts sent a Christmas message from the Moon, immortalised at **https://bit.ly/pe-apr23-nasa2** and that month Frank Hyde described NASA's launch of their largest space observatory satellite, the Orbiting Astronomical Observatory which was an early 'Hubble' space telescope. The 2-tonne platform bristled with 11 telescopes that would plot the stars, and it had an expected lifespan of just six months. Less widely known in the 1960s was the US Air Force plan to launch a secret manned spy platform called MOL, which was eventually cancelled due to budget restraints, see: **https://bit.ly/pe-apr23-mol**

Weather satellites were already being launched into sun-stationary orbits 50 years ago in 1973, and Pioneer satellites were heading towards Venus by 1978.

NASA's modified Boeing 747 Shuttle Carrier Aircraft with the Space Shuttle Endeavour on top lifts off to begin its ferry flight back to the Kennedy Space Center in Florida. (Image: NASA Photo)

Frank Hyde was an extraordinary British radio astronomer who has been recognised for constructing the largest amateur radio observatory in 1960s Britain. He would work with the Jodrell Bank observatory and it's said his work influenced some of the experiments on board NASA's Pioneer missions. He also knew the popular, if slightly eccentric, British astronomer Patrick Moore, who became well known for the BBC TV *Sky at Night* series, with Frank Hyde also appearing occasionally on the same programme. Patrick Moore believed he was possibly the only person to have met the first aviator, Orville Wright, the first man in space, Yuri Gagarin, and the first man on the moon, Neil Armstrong. He interviewed astronaut Neil Armstrong in 1970, which can be seen at: **https://youtu.be/EIPn_iuLPA4**



Sadly, the brilliant Frank Hyde hit financial hard times, and his own radio and TV repair business eventually folded. His latter years were not exactly covered in glory either, and his close relationship with the British Astronomical Association (BAA) terminated on a sour note. He died in March 1984 aged 75, and the founding editor of *Practical Electronics*, Fred Bennett, to whom I owe my electronics writing career, wrote an obituary in Frank Hyde's final column, published in the June 1984 edition. Patrick Moore then took over the *Spacewatch* column. I managed to unearth an excellent biography of Frank Hyde, originally published in the *BAA Journal*, at: **https://bit.ly/pe-apr23-fh1** and there is a little more local history at: **https://bit.ly/pe-apr23-fh2**

If you're at all interested in astronomy, it's worth considering becoming a member of the BAA – more details can be found at **https://britastro.org**

A 50-year milestone

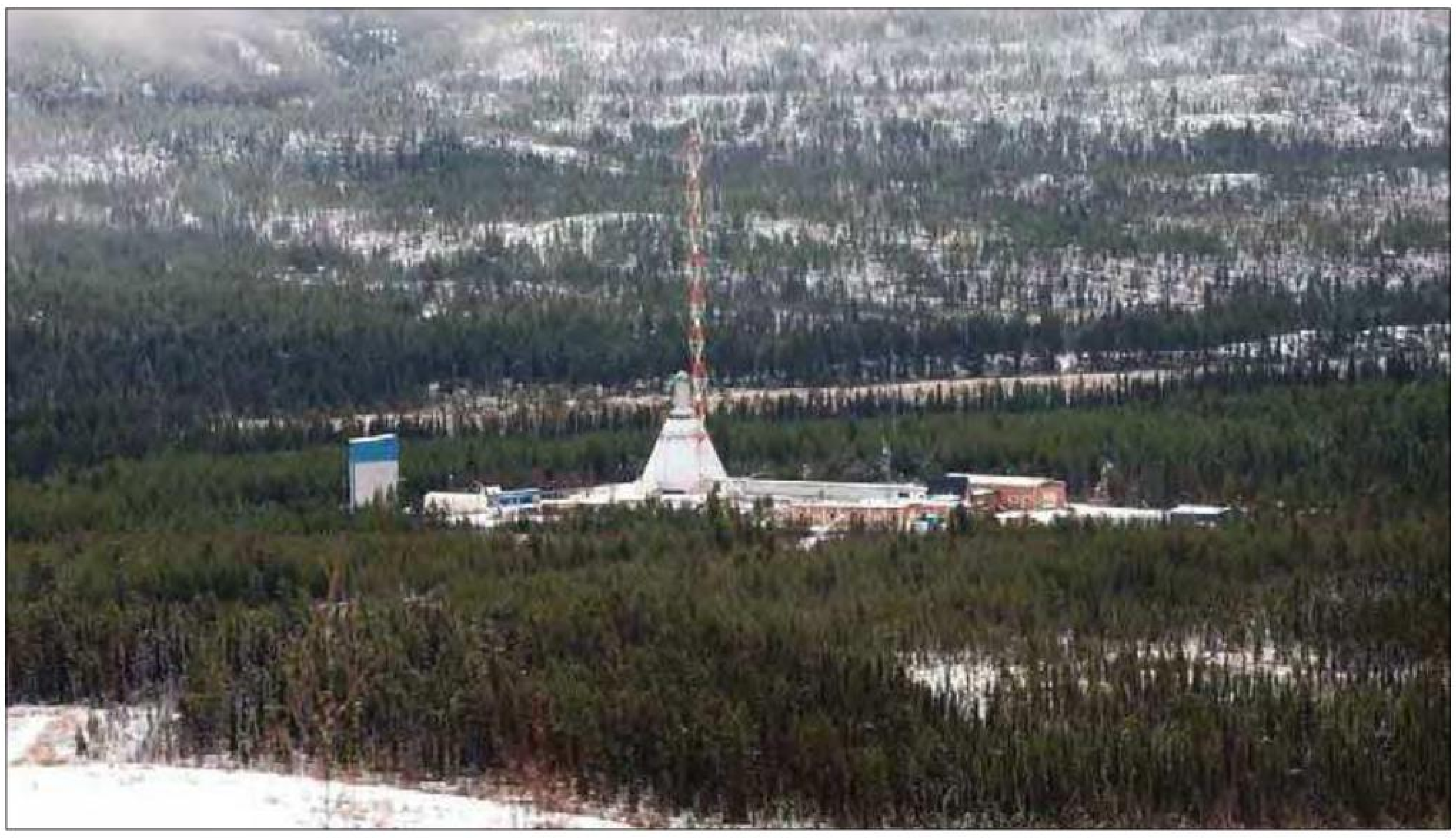
Thumbing through old issues I was struck by the way the Spacewatch column graphic changed over the years: a timestamp reflecting the progress made in man's desire to reach the stars. The magazine artwork incorporated the Lunar Module, before being updated to show a new type of 'space plane' atop a Boeing 747 instead, before changing to a space vehicle flying solo in space.

It's sometimes humbling and hard to believe that the NASA space shuttle program first took shape more than half a century ago, when the idea of building a re-usable space cargo plane gained ground. The vehicles, originally called 'orbiters', were extensively flight-tested as gliders and transported around using 'shuttle carrier aircraft' based on two specially adapted Boeing 747s. The *Enterprise* was an engine-less prototype orbiter, while *Columbia* was the first orbiter that would be launched into space. I was glued to the TV watching space shuttle test flights glide back to earth.

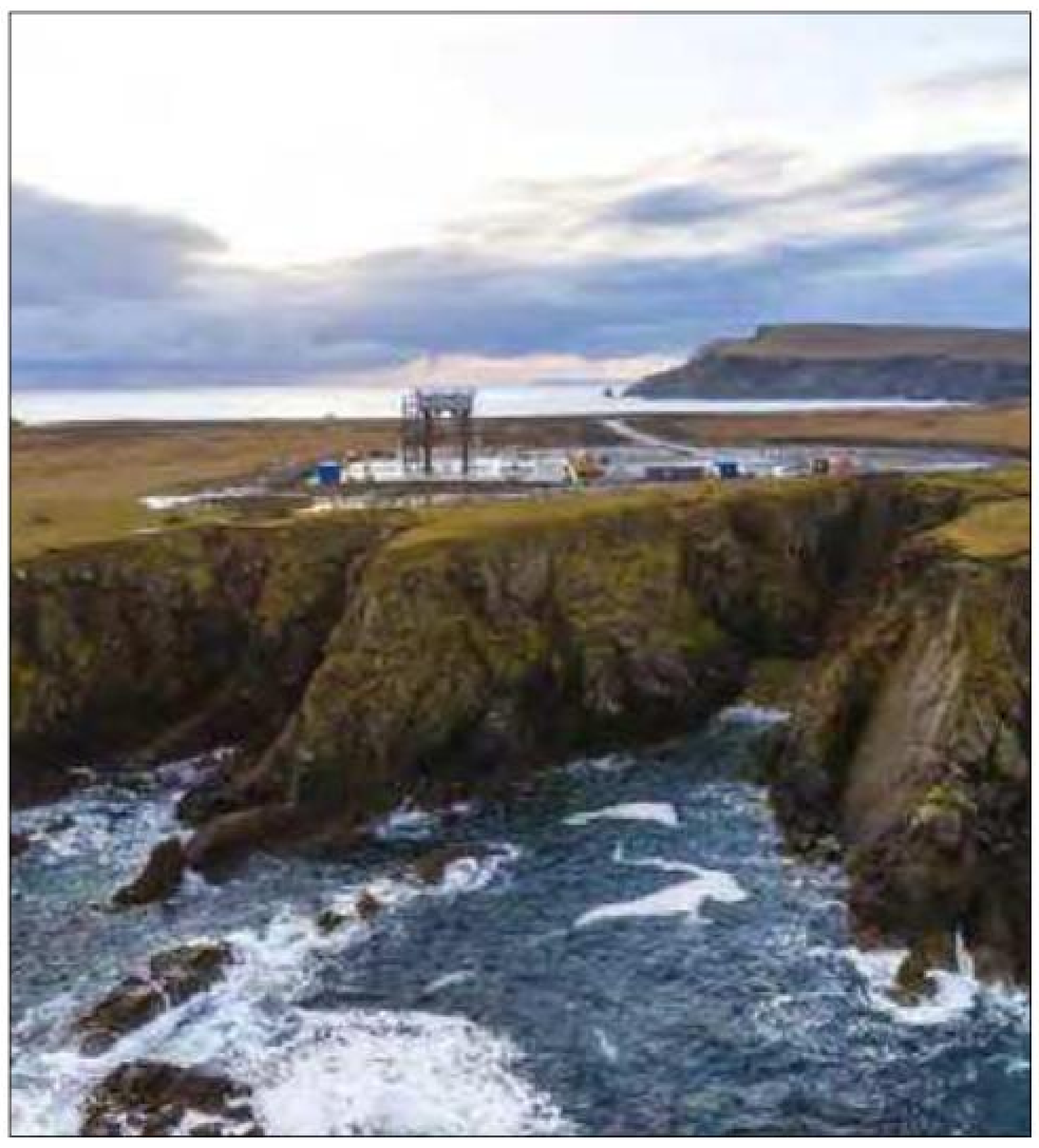
The connection with the Boeing 747 and space shuttle *Columbia* is particularly poignant this month as the final Boeing 747 'Queen of the Skies' to be made was delivered on 1 February to the airline Atlas Air. The plane's flight was commemorated when its flight path traced out '747', as shown in a BBC news report at: **https://bit.ly/pe-apr23-747**

Another milestone in space exploration was passed this month – it's exactly 20 years ago in 2003 that the *Columbia* space shuttle disintegrated during re-entry, leaving no survivors. This came almost exactly 17 years after the *Challenger* launch disaster of 1986. Following the *Columbia* disaster, space shuttle missions were suspended for two years before resuming, and the increasingly elderly shuttle fleet was grounded for good in 2011.

Readers who enjoy looking at the nuts and bolts of legacy space hardware might like to check out some of



Opening for business: Spaceport Sweden is readying to enter the microsatellite launching business with an expanded pad located at Esrange, just north of the Arctic Circle.



On the rocks: SaxaVord has attracted attention from Rocket Factory Augsburg (RFA), with one launch pad being snapped up by the German rocket launcher.

the *Owner's Workshop Manuals* published by Haynes – famed for their car repair manuals – which includes the Saturn V and Space Shuttle. The *Apollo 11 Manual* includes details of the first moon landing. You can buy it via the usual outlets or direct from: **https://bit.ly/pe-apr23-man**

Other space news

Still on the subject of space launches and Boeing 747s, investigations are continuing into finding the reason why Virgin Orbit's first satellite launch from Britain failed during the 'Start Me Up' mission (see last month). Virgin Orbit stated that every other satellite they have launched had reached orbit successfully, and they are pressing on with their next launch from California. Virgin Orbit's CEO is quoted as saying that the mission failure was possibly caused by a dislodged filter shutting off the first stage prematurely. More flights from Cornwall will follow later this year.

California-based ABL Space Systems (**https://ablspacesystems.com**) is a low-profile startup rocket lobber that not many people have heard of, but they are touting for business with the likes of Amazon's Kuiper LEO satellite program, and they've raised over $400m in funding, according to Crunchbase. In January, ABL attempted to launch their first RS1 rocket from Alaska Spaceport, but the rocket fell back to earth 11 seconds after launching. There is no video, but the PR states that a loss of power just after 10 seconds shut down all nine engines and the rocket fell back down laden with 95% of its fuel, creating 'an energetic explosion'. Various storage tanks, ground-based equipment and hangars were destroyed, they added.

Spaceport Sweden recently cut the ribbon on their new launching facility which is now open for business. The newly expanded Esrange Space Center site on the very northernmost edge of Sweden is the first such facility on mainland Europe and has previously been used for launching 'sounding rockets' (smaller scientific test and measurement rockets), but now has its eyes on the satellite business. More details are at: **https://sscspace.com/esrange/**

Yet more competition for microsatellite launchers is arriving on the market, as Germany's Rocket Factory Augsburg (RFA) launching service has signed up with SaxaVord Spaceport for exclusive use of one of its three proposed launch pads, starting by the year end. SaxaVord is based in the Shetland Islands and is Britain's northernmost launching site. More info at: **https://saxavord.com/r/**

Other news

My thanks go to reader Stephen Horsman who followed up on my February column: 'I enjoy your columns and have just got round to reading your Feb 23 column re. backup technology. I was an IT manager in the early 2000s and got sick of restoring the tape catalogues from tape drives to get one file back, and I started using Drive Snapshot to disc image to USB Hard drives. It was/is written in machine code and could be booted from a floppy, or USB drive these days. Images can be mounted, and files dragged and dropped very easily. I still use it to this day and it's well worth checking out.

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Regards, Stephen.' For more details, see: **http://drivesnapshot.de**

Thanks for the suggestion, Stephen. Another backup product suited to the IT enthusiast that came recommended is Casper by Future Systems Solutions. Various versions are available, see: **www.fssdev.com/products/casper**

Users of barcode scanner apps have been alerted to the risks of scanning untrusted or dodgy QR codes, as they could link through to malware or scam sites. The problem of 'QR Jacking' is increasing because ordinary users trust QR codes implicitly, but they could link through to a fraudster's site that may attempt to steal logins, IDs or other sensitive data. In one reported case, bogus QR codes were stuck on local authority parking meters encouraging drivers to scan them and pay – but the bogus website merely stole their cash instead. Look closely at QR codes stuck on meters, signs or even authentic-looking forms and if you're unsure, treat them as dodgy-looking file attachments and steer clear.

Virtually unusable

I'm getting increasingly annoyed by pop-ups that appear on my smartphone that contain a phoney 'X' [close] icon. They're a form of click-bait which, instead of dismissing the pop-up, actually clicks through to an advert instead, thereby earning the advertiser some revenue. In a self-defeating move to monetise mobile content, increasing numbers of news portal websites are becoming unusable when viewed on a small screen – blizzards of pop-ups for privacy, cookies, special offers and other opt-ins fill the screen, sometimes locking up the display as well. The problem has reached saturation point. Also likely to incur my wrath is the plethora of over-designed websites that have an 'X' [close] icon sited well out of the current field of view, perhaps greyed out somewhere in a nearby coloured panel so you have to hunt around for it. This 'designer-itis' idiocy only ever makes the web less accessible and harder to use for everybody, and if anything, it turns people off.

Amid a slew of redundancies and cutbacks, and with shoppers starting to re-discover traditional bricks-and-mortar High Street retailers, Amazon Smile closed permanently on 20 February. The service donated a small portion from a buyer's purchase to their appointed charity at no extra cost, but the programme had 'not grown to create the impact that we had originally hoped', Amazon explained. A new 'Amazon for Charities' store service will allow charities to sell wares on Amazon and collect 100% of profits, but only a handful of big names have signed up so far. Amazon raised £18.5m for UK charities in total, and £382m worldwide.

Long predicted in *Net Work*, some British consumers were for the first time offered an energy rebate for reducing consumption in January in order to ease peak period demand on the energy network. The 'Demand Flexibility Service' requires a smart meter and 30-minute reporting of usage, and could result in a rebate of a few pounds.

Australian start-up Recharge Industries appears to have rescued the collapsed BritishVolt battery gigafactory after the business fell into administration. The giant factory, one of the largest in Britain, will produce batteries for electric vehicles and the military.

That's all for this month's column. Readers will find an online summary with links on the *Net Work* blog of our website at: **www.electronpublishing.com** – see you next month!

The author can be reached at:
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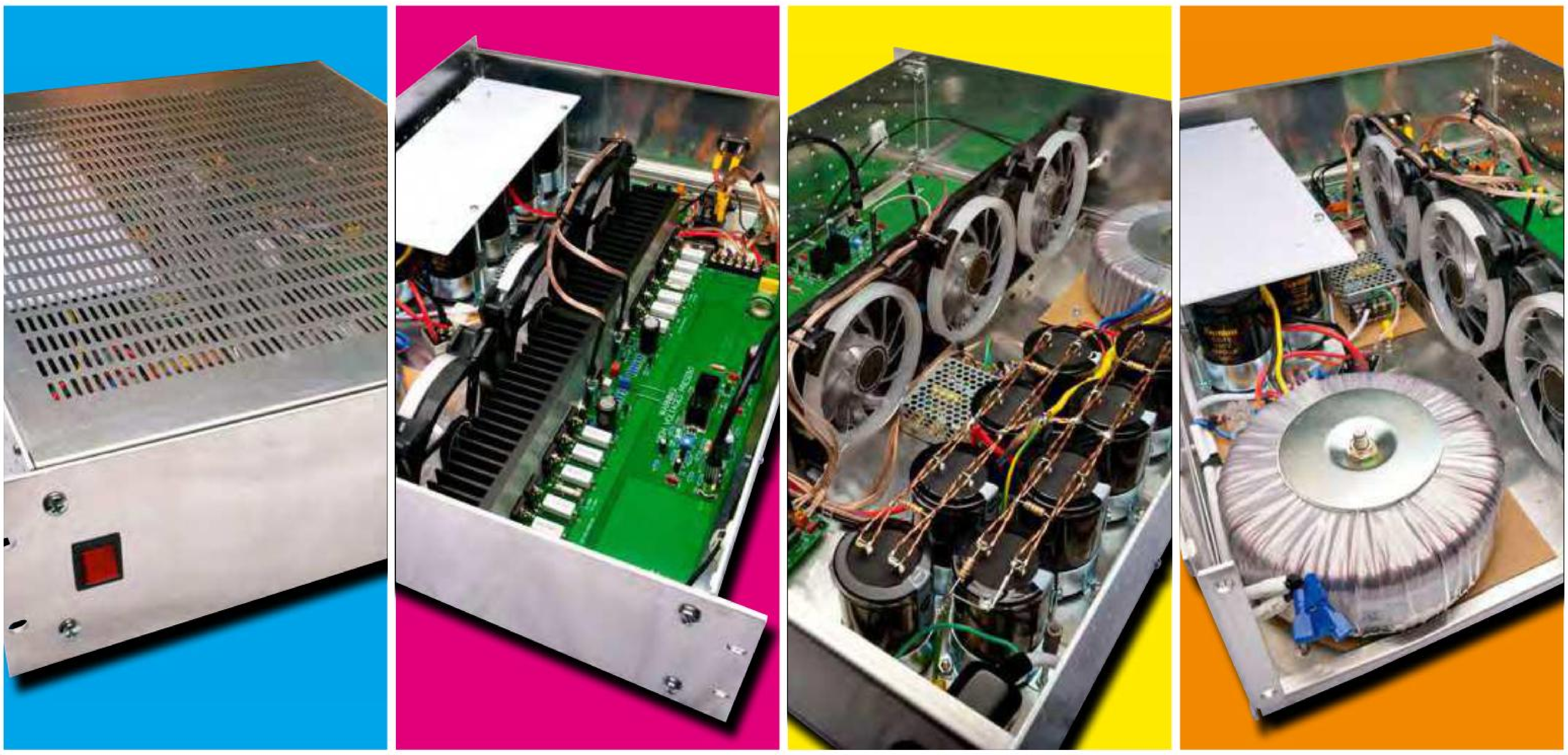
500 WATTS POWER AMPLIFIER

PART 1

BY JOHN CLARKE



This large power amplifier produces big, clear sound with low noise and distortion. It delivers 500W RMS into a 4Ω load and 270W into an 8Ω load. It has been designed to be very robust and includes load line protection for the output transistors and speed-controlled fan cooling that remains off until needed. With two of these, you could deliver 1000W into a single 8Ω loudspeaker. Good luck finding one that will handle that much power!

FEATURES AND SPECIFICATIONS

Output power	>500W into 4Ω, >270W into 8Ω – see Fig.3
Frequency response	+0, –0.1dB over 20Hz-20kHz (–3dB @ 97kHz) – see Fig.1
Signal-to-noise ratio	112dB with respect to 500W into 4Ω or 250W into 8Ω
Total harmonic distortion (4Ω)	<0.005% @ 1kHz for 1.5-350W – see Fig.2 and Fig. 3
Total harmonic distortion (8Ω)	<0.025% @ 1kHz for 2-270W – see Fig.2 and Fig.3
Input impedance	10kΩ || 4.7nF
Input sensitivity	1.015V RMS for 500W into 4Ω, 1.055V RMS for 270W into 8Ω
Power supply	±80V nominal from an 800VA 55-0-55V transformer
Quiescent current/power	94mA, 15W
Protection	DC fuses, dual-slope thermal tracking, SOA current limiting, output clamping diodes
Other features	output offset nulling, blown-fuse indicators, onboard power indicator

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Our 500W amplifier is big in several ways. It is physically big, requiring two heatsinks stacked end-to-end to keep the temperature under control. It requires a significant power supply using an 800VA transformer, and the amplifier and power supply fit into a three rack unit (3RU) rack case, again of rather large dimensions.

It does deliver a prodigious amount of power. It is ideal for a public address system where high power can be necessary for sound reinforcement in a large venue. It is also well-suited to driving inefficient loudspeakers. As noted above, used in bridge mode, it could deliver just over 1000W per channel. Build two pairs for a sound system so massive, it would need to be plugged into two different mains power points!

Two of these amplifiers could also be the basis of an amazing stereo system for use in a large listening room.

You might think that a 500W per channel stereo system is just too much power. Whether that is true depends on what sort of music you like listening to and how efficient your loudspeakers are. If you like rock music with its somewhat limited dynamic range, then with this amplifier, you will be able to play it loud. That makes it ideal for music that just has to be loud to be enjoyed.

But please don't deafen yourself with the extreme sound levels possible with such a large amplifier. You might also need to provide ear protection for your neighbours!

It isn't just for rockers, either. Classical music requires lots of power as well. This is not because the performance is necessarily loud, but it allows the wide dynamic range in volume of concert hall performances to be replicated.

You want high power without distortion to produce the high peak volume levels of the performance, like massive kettle drum hits or pipe organ stings, with low noise from the amplifier so that it does not drown out the whisper-quiet passages.

Big power like this does not come easily. The amplifier uses 12 output transistors and they are all mounted on a 400mm-wide heatsink. The main circuit board is also significant at 402 x 124mm. The final installation within the 3U rack enclosure measures 559mm x 432mm x 133.5mm and weighs just over 12kg.

This article will concentrate on describing the *Amplifier Module* circuit. Over the next two months, we'll also give the full assembly details for this Module, plus describe a suitable power supply. Then we'll show you how to build the Module, power supply, speed-controlled fan cooling (which switches off at light loads), speaker protector and clip detector – all into an aluminium 3RU rack-mountable chassis.

Performance

The main performance parameters are summarised in the specification panel and Fig.1 to Fig.3. These indicate that just because a power amplifier delivers a lot of power, that does not mean that it cannot deliver high performance as well.

For one, the frequency response is ruler-flat from 20Hz to 20kHz, a mere 0.1dB down in response at 20kHz. Power into 4Ω is a genuine 500W. At typical power levels, between 1.5W and 350W, the total harmonic distortion plus noise (THD+N) is below 0.007% at 1kHz.

For an 8Ω load, maximum power is around 270W until the onset of clipping, with <0.004% THD+N at 1kHz at more typical power levels from 1W to 200W. Under ideal conditions, it's close to what we'd call 'CD quality' at around 0.002% THD+N.

As you can see from Fig.2, distortion rises somewhat with frequency; in fact, it's considerably lower than quoted above at more typical audio frequency ranges for most instruments of around 100-500Hz. Above 1kHz, distortion rises modestly, although it's still relatively low even by 10kHz, above which the filters in our test equipment start attenuating the harmonics.

The THD+N result of under 0.05% for 266W into 3Ω shows that the performance of this amplifier does not degrade significantly even under harsh conditions, driving lower load impedances than you'd expect to see with most high-power 4Ω loudspeakers.

Perhaps the most important aspect of this high-power amplifier is the very good signal-to-noise ratio of 112dB. This means that you can get a very high output level, including loud transients, without an annoying background hiss the rest of the time.

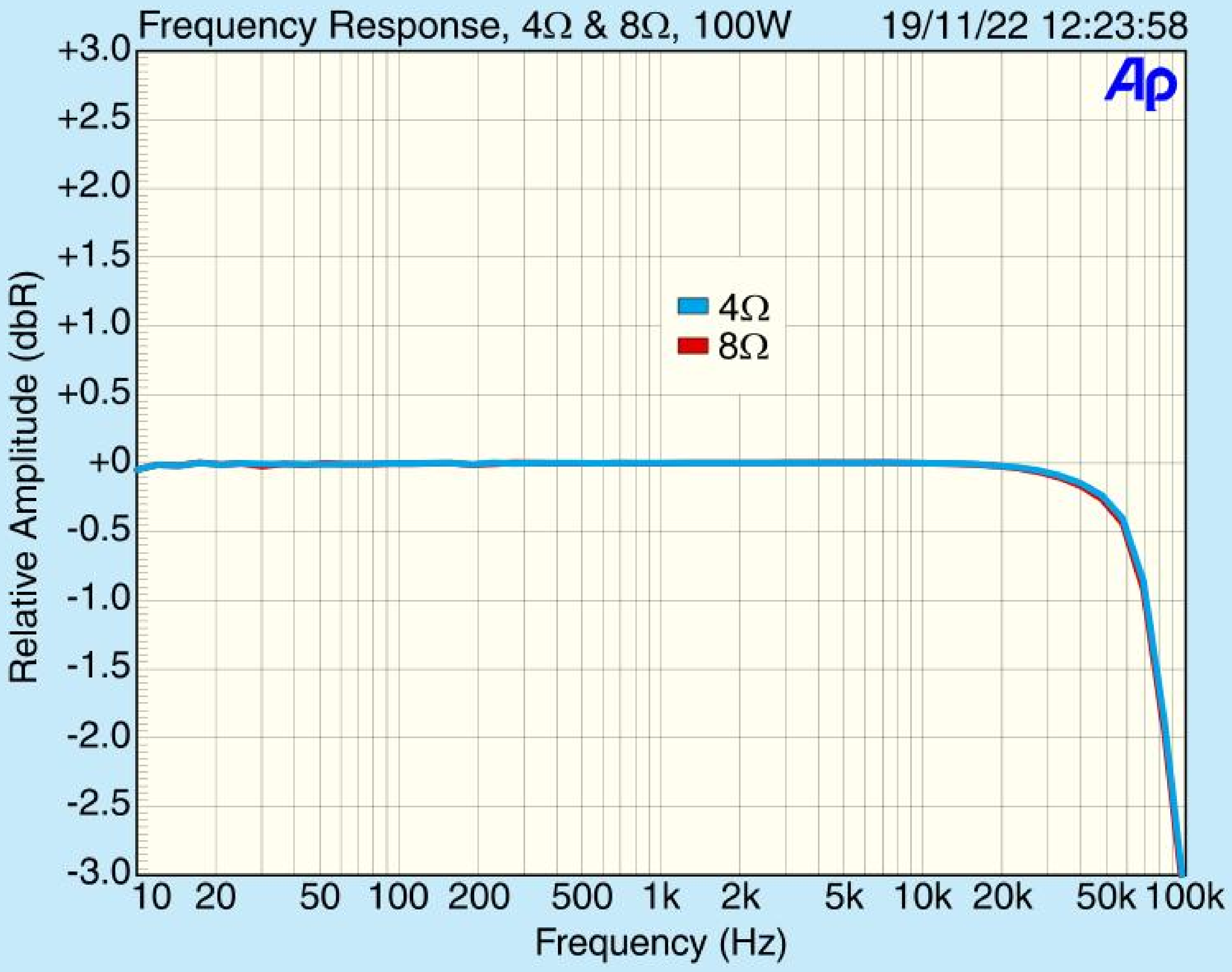


Fig.1: the frequency response of this amplifier is exceptionally flat, varying by less than 1/20dB between 20Hz and 20kHz. The upper –3dB point is just short of 100kHz. While the lower –3dB point is not visible in this plot, it's likely around 1Hz. An active subsonic pre-filter would be necessary to prevent over-extension if you're using this amp to drive a subwoofer directly.

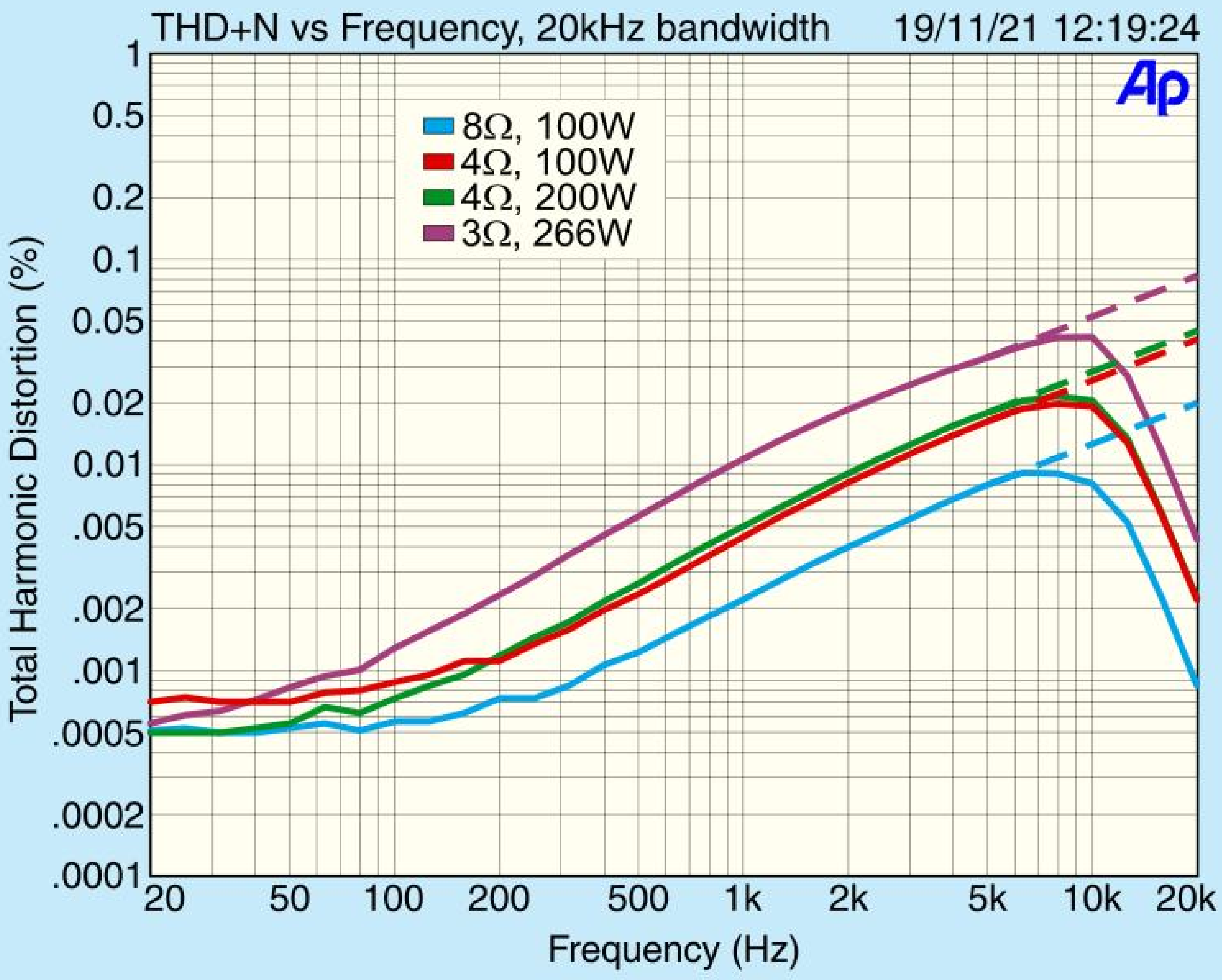
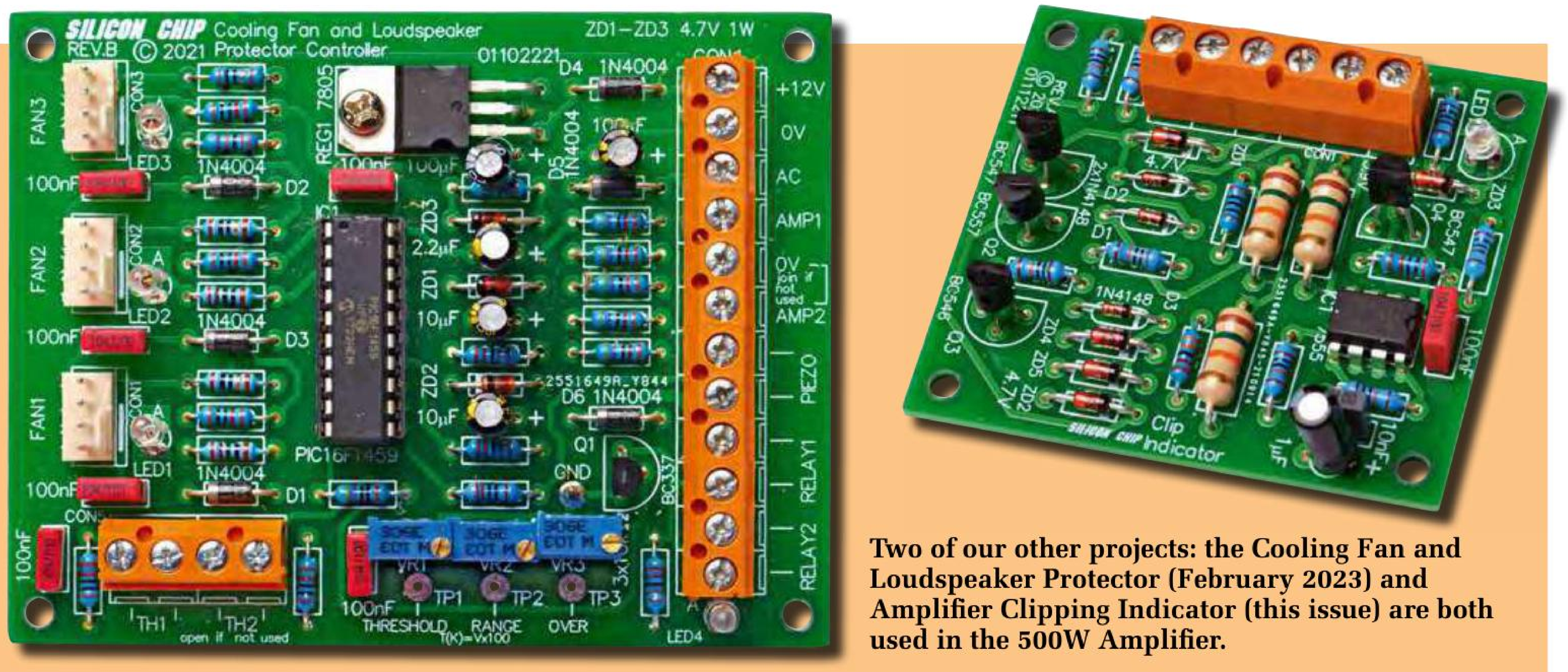


Fig.2: THD+N plots for 8W, 4W and 3W loads (two different power levels are shown for 4W) with 20Hz-22kHz bandwidth. You can see that the base distortion largely depends on the load impedance, and it rises steadily with frequency above about 100Hz. The 3W curve is mainly presented as a 'worst-case scenario' and shows that it can drive very low load impedances without too much difficulty.



Two of our other projects: the Cooling Fan and Loudspeaker Protector (February 2023) and Amplifier Clipping Indicator (this issue) are both used in the 500W Amplifier.

Circuit details

The full circuit diagram is shown in Fig.4. Aside from the large number of output transistors, the circuit is similar in configuration to many of our previous amplifiers, including the Ultra-LD Mk.2 (August and September 2010).

One major difference is the addition of safe operating area (SOA) protection for the output transistors. This helps prevent damage to them if the amplifier is short-circuited or presented with a load that exceeds their safe operating area (SOA). This is not just protection against a short circuit; it works over the entire operating range of the amplifier.

We've heard it stated in the past that SOA protection degrades the performance of an amplifier, but we tested this one with it in-circuit and disconnected, and we couldn't measure any differences. So you don't need to be concerned about its impact on sound quality.

The supply rails are ±80V or 160V in total. This high voltage requires rugged transistors, particularly the output and driver transistors, which need a large SOA. We could have used the NJL3281D/NJL3282D ThermalTrak transistors as used in previous amplifiers. However, we would have needed 12 of these transistors per side or 24 in total to ensure it was robust.

The ThermalTrak transistors have two main advantages: good linearity and each device includes a separate diode for biasing. The diode within the transistor package allows the quiescent (idle) current to be controlled accurately with temperature variations. Unfortunately, the sheer number of these transistors required would make the amplifier impractically large and expensive, so they are unsuitable.

Instead, we are using MJW21196/MJW21195 transistors, with only six required per side, thanks to their generous SOA curves.

The input signal is AC-coupled via a 47µF non-polarised electrolytic and high-frequency stopper components, ferrite bead FB1 and a 22Ω resistor to the base of transistor Q1. The 22Ω input resistor and 4.7nF capacitor constitute a low-pass filter with a –6dB/octave roll-off above 1.5MHz.

Q1 is part of the input differential pair of Q1 and Q2, which are Toshiba 2SA1312 PNP low-noise transistors.

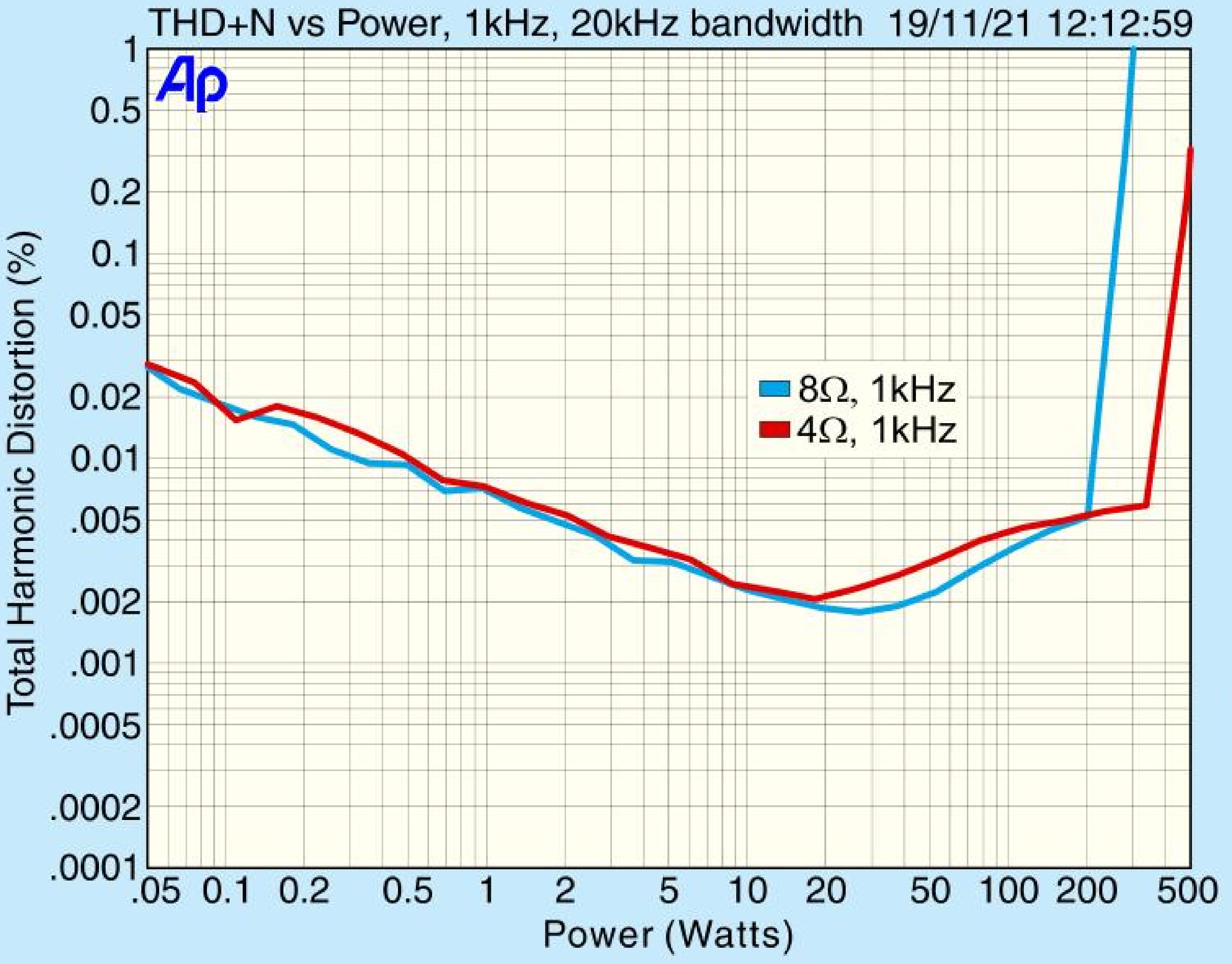
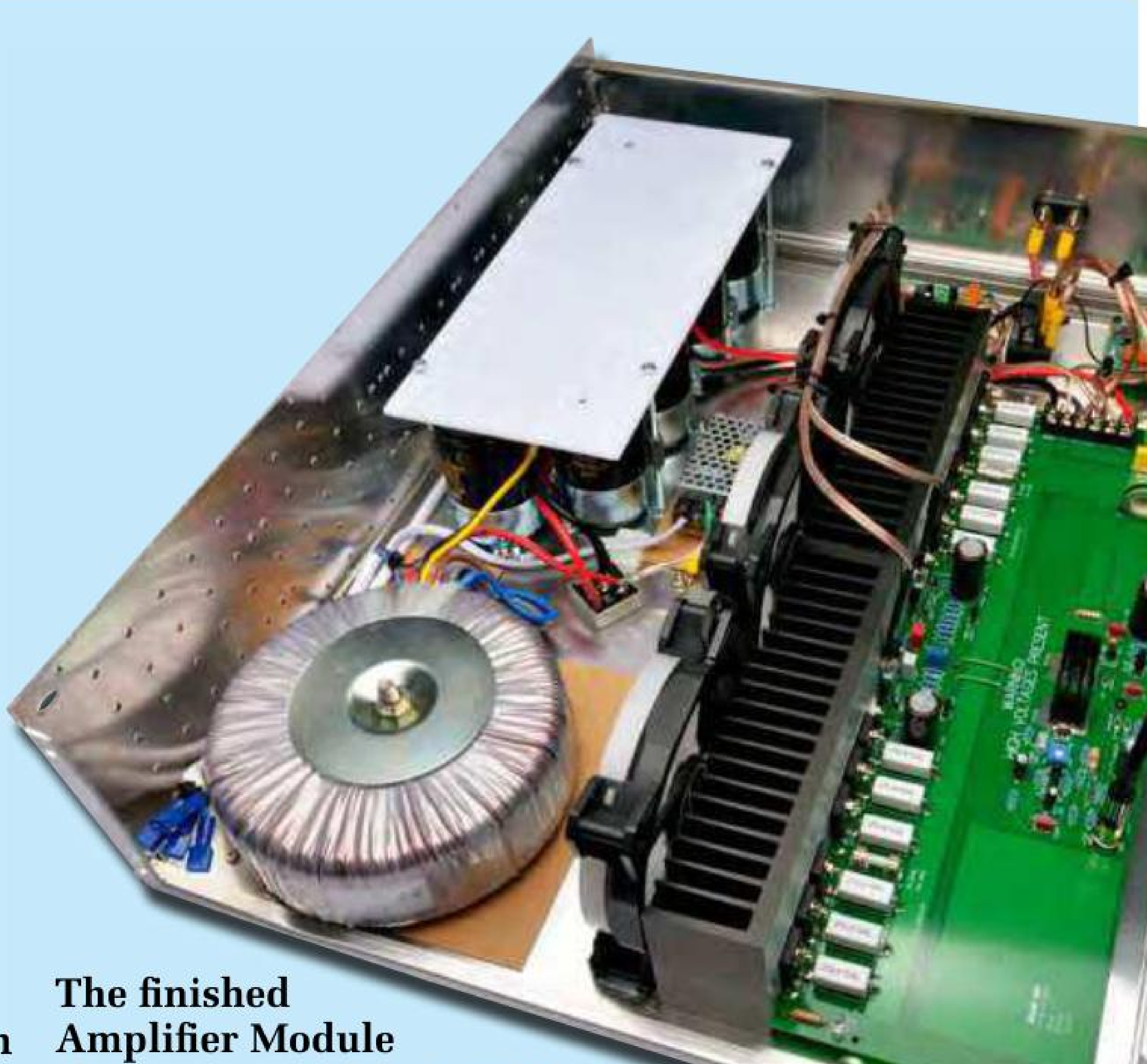


Fig.3: THD+N vs power at 1kHz. Distortion starts to rise above 350W for 4Ω loads but it delivers 500W without gross distortion (and even more on a short-term basis). The performance is pretty good in the middle power range, from a few watts to a couple of hundred watts; it will give 'CD quality' into 8Ω up to about 200W. Double the numbers on the horizontal axis and check the 4Ω curve for 8Ω bridged performance!



The finished Amplifier Module shown mounted in its 3RU case with heatsink and fans. Note the 120mm PWM fans attached to the heatsink, as anything larger wouldn't fit in the case with its lid on.

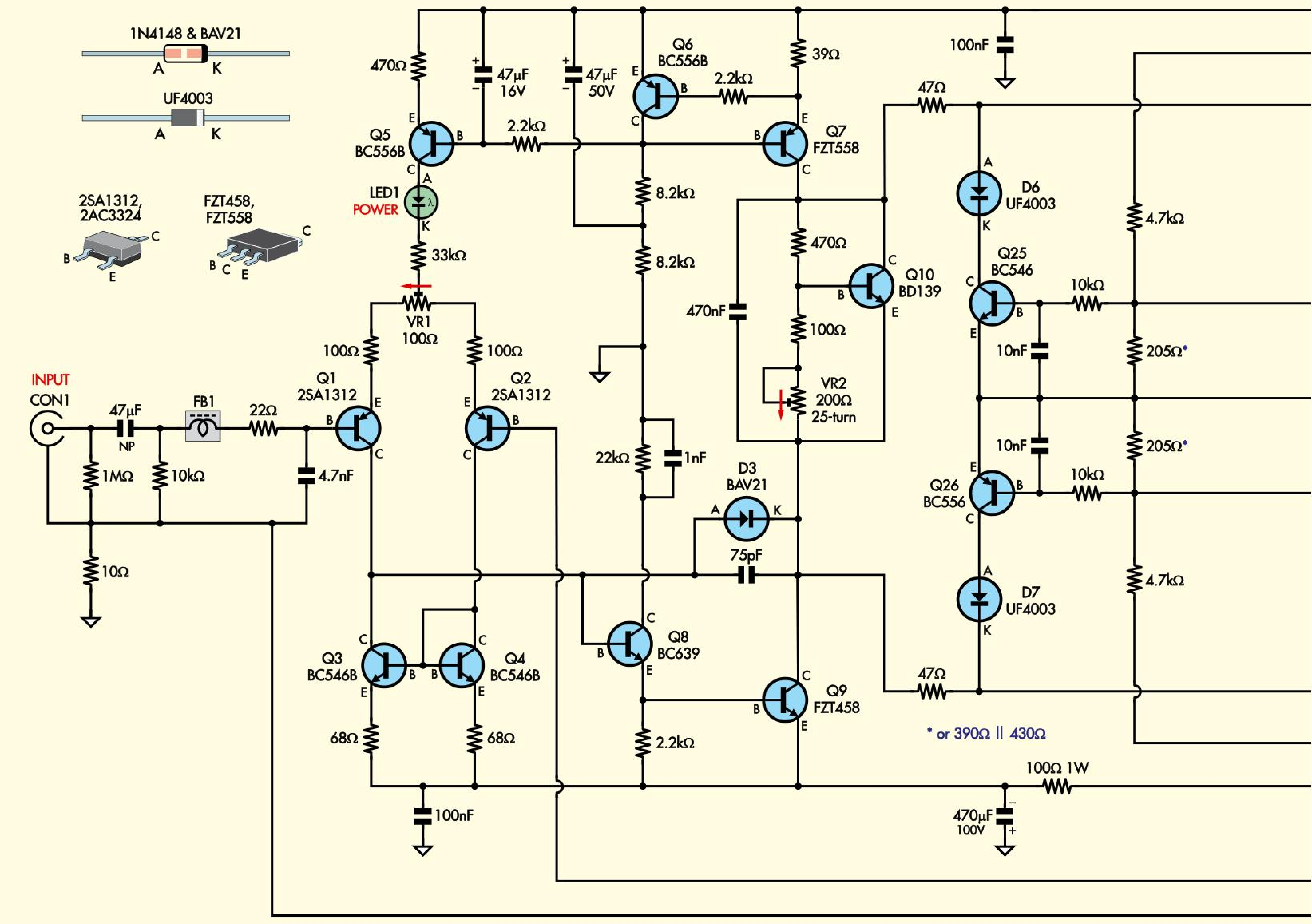

1N4148 & BAV21
A
K
UF4003
A
K
2SA1312,
2AC3324
B
C
E
FZT458,
FZT558
B
C
E
C
470Ω
47µF
16V
47µF
50V
Q6
BC556B
2.2kΩ
39Ω
100nF
Q5
BC556B
2.2kΩ
Q7
FZT558
47Ω
LED1
POWER
8.2kΩ
D6
UF4003
4.7kΩ
33kΩ
8.2kΩ
470Ω
Q10
BD139
Q25
BC546
10kΩ
VR1
100Ω
470nF
100Ω
10nF
205Ω*
100Ω
100Ω
VR2
200Ω
25-turn
INPUT
CON1
47µF
NP
FB1
22Ω
Q1
2SA1312
Q2
2SA1312
10nF
205Ω*
22kΩ
1nF
D3
BAV21
Q26
BC556
10kΩ
1MΩ
10kΩ
4.7nF
10Ω
75pF
D7
UF4003
4.7kΩ
Q3
BC546B
Q4
BC546B
Q8
BC639
Q9
FZT458
47Ω
68Ω
68Ω
2.2kΩ
* or 390Ω || 430Ω
100Ω 1W
100nF
470µF
100V

Fig.4: the main difference between this amplifier and our last few designs is the sheer number of output devices (six pairs) and the addition of SOA/load line protection circuitry. This protection circuitry is based on voltage references REF1 and REF2, transistors Q25 and Q26 and the associated resistor network, including the series of 3.3kΩ resistors connected to the emitter of each output transistor.

These are responsible for the very low residual noise of the amplifier.

2SA1312 transistors are becoming somewhat challenging to get, but we have secured a good supply for our readers as we couldn't find any suitable alternatives – see the parts list for our sourcing recommendation.

(*Editor's note – the practice of manufacturers discontinuing components with no direct replacement is very frustrating, and it has bitten us several times.*)

The bias resistor for Q1 and the series feedback resistor to the base of Q2 are set to a relatively low value of 10kΩ to minimise signal source impedance and thereby reduce thermal noise. The 10kΩ input resistance and the 47µF input capacitor provide a low-frequency roll-off at 0.34Hz.

The amplifier gain is set by the ratio of the 10kΩ and 220Ω feedback resistors at the base of Q2. This gain is 46 times (33dB), while the 2200µF capacitor sets the low-frequency roll-off (–3dB point) in the feedback loop to 0.33Hz. The relatively high gain helps to keep the amplifier stable and makes the input sensitivity reasonable at around 1V RMS for full-power output.

Coupling capacitors

The high-value electrolytic capacitors for the input coupling (47µF) and feedback (2200µF) networks eliminate any effects of capacitor distortion in the audio pass-band and also minimise the source impedance.

To explain, if we use a smaller input capacitor at say 2.2µF, its impedance will be 1447Ω at 50Hz. This will only have a small effect on the audio frequency response but represents a substantial increase in the source impedance at low frequencies. By contrast, the 47µF input capacitor we used has an impedance of only 67.7Ω at 50Hz.

This also means that the voltage across these capacitors is minimal compared to the audio signals, so the inherent non-linearity of electrolytic capacitors does not matter.

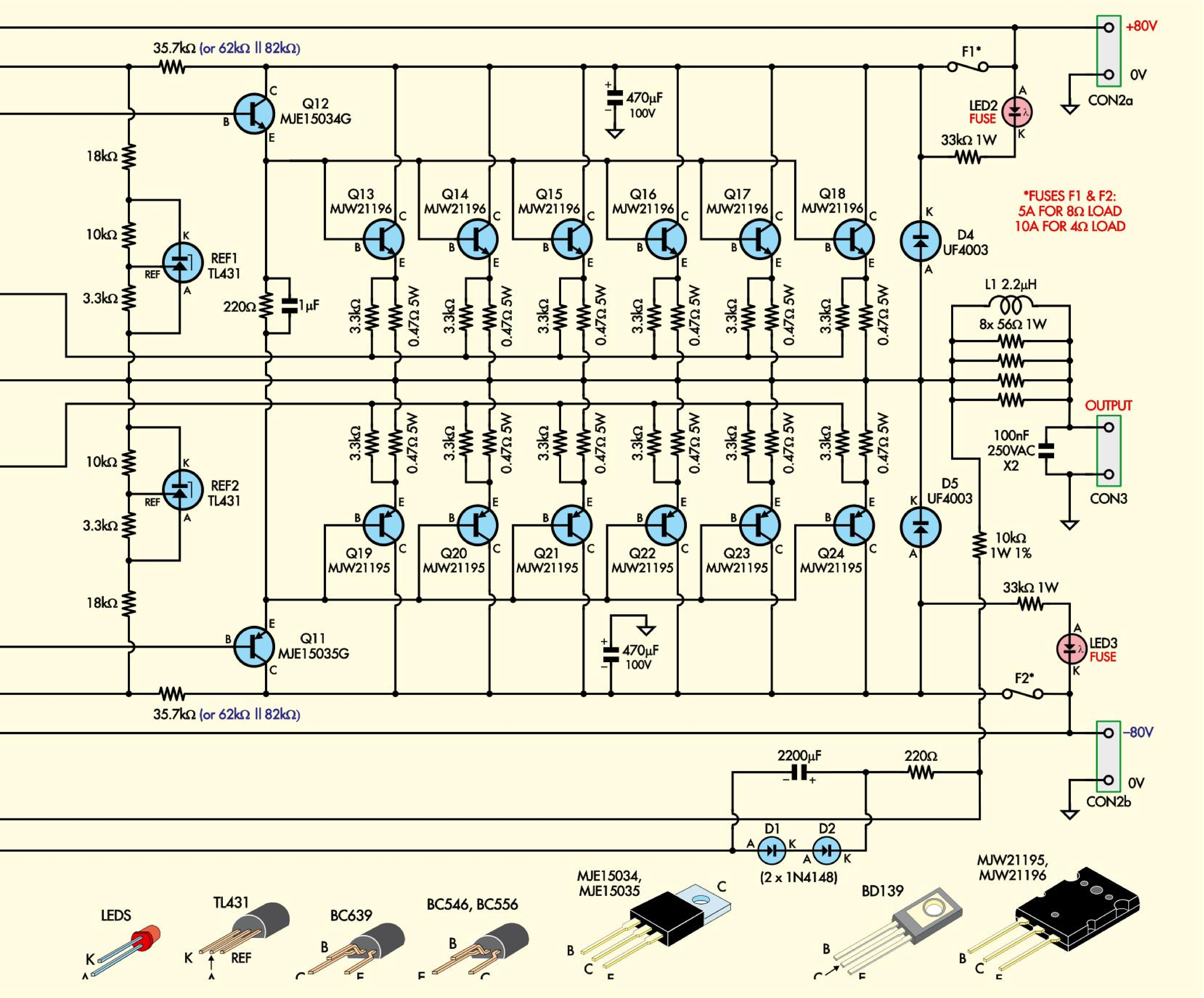
Diodes D1 and D2 are included across the 2200µF feedback capacitor as insurance against possible damage if the amplifier suffers a fault where the output is pulled to the –80V rail. In this circumstance, the capacitor would have a significant reverse voltage.

We use two diodes instead of one to ensure that there is no audio distortion due to the non-linear effects of a single diode junction at the maximum feedback signal level of about 1V peak. This prevents diode conduction under normal operating conditions.

Voltage amplification stage

Most of the amplifier's voltage gain is provided by Q9, fed via emitter-follower Q8 from the collector of Q1. Together, these transistors form the voltage amplification stage (VAS). Q8 buffers the collector of Q1 to minimise non-linearity.

Q9 is operated without an emitter resistor to maximise gain and also maximise its output voltage swing.


35.7kΩ (or 62kΩ || 82kΩ)
Q12
MJE15034G
18kΩ
10kΩ
REF1
TL431
REF
3.3kΩ
220Ω
1μF
470μF
100V
Q13 MJW21196
Q14 MJW21196
Q15 MJW21196
Q16 MJW21196
Q17 MJW21196
Q18 MJW21196
3.3kΩ
0.47Ω 5W
F1*
+80V
0V
CON2a
LED2
FUSE
33kΩ 1W
D4
UF4003
*FUSES F1 & F2:
5A FOR 8Ω LOAD
10A FOR 4Ω LOAD
L1 2.2μH
8x 56Ω 1W
OUTPUT
100nF
250VAC
X2
CON3
D5
UF4003
10kΩ
1W 1%
REF2
TL431
Q19 MJW21195
Q20 MJW21195
Q21 MJW21195
Q22 MJW21195
Q23 MJW21195
Q24 MJW21195
Q11
MJE15035G
LED3
FUSE
F2*
–80V
CON2b
2200μF
220Ω
D1
D2
(2 x 1N4148)
LEDS
TL431
BC639
BC546, BC556
MJE15034,
MJE15035
BD139
MJW21195,
MJW21196
A
K
B
C
E

Maximum voltage swing is required from the voltage amplifier stage to obtain as much power as we can from the output stages.

Current mirror

The collector loads of Q1 and Q2 are NPN transistors Q3 and Q4 which operate as a current mirror. Q4 acts as a sharp cutoff diode, providing a voltage at the base of Q3 equal to the base-emitter voltage drop of Q4 (about 0.6V) plus the voltage drop across its 68Ω emitter resistor.

If Q2 draws more than its share of emitter current from Q5, the voltage at the base of Q3 increases, so Q3's collector current also rises. This forces Q1 to pull a bit more current and stops Q2 from taking more than its fair share. As Q3 mirrors the current of Q4, Q1 is provided with a collector load that has a higher impedance than would otherwise be the case.

The result is increased gain and improved linearity from the differential input stage.

Similarly, the collector load for Q9 is a constant-current load comprising transistors Q6 and Q7. Interestingly, the base bias voltage for constant current source Q5 is also set by Q6. Q5 is the constant current tail for the input differential pair of Q1 and Q2, and it sets the current through these transistors. LED1 is connected to this circuit as a 'free' power-on indicator.

The reason for the somewhat complicated bias network for Q5, Q6 and Q7 is to produce a major improvement in the power supply rejection ratio (PSRR) of the amplifier. Similarly, the PSRR is improved by the bypass filter network consisting of the 100Ω 1W resistor and 470μF 100V capacitor in the negative supply rail.

Why is PSRR so important? Because this amplifier runs in class-AB, it pulls large asymmetric currents from the positive and negative supply rails. The currents are asymmetric in the sense that it's pulling from one or the other at any given time; the waveforms will be a similar shape for a sinewave, just time-shifted compared to each other.

So, for example, when the positive half of the output stage (Q13 to Q18) conducts, the current waveform is effectively the positive half-wave of the signal waveform; ie, rectification occurs. Similarly, when the negative half of the output stage (Q19 to Q24) conducts, the current is the negative half-wave of the signal.

So we have half-wave rectification ripple of the signal superimposed on the supply rails, as well as the 100Hz ripple from the power supply itself. And while the PSRR of an amplifier can be very high at low frequencies, it is always worse at high frequencies. If these ripple voltages can get into the earlier stages of the amplifier, they will cause distortion, so we need to minimise them there.

Diode D3 is included to improve recovery performance when the amplifier is driven into hard clipping. It makes the recovery from negative

Parts List – 500W Amplifier Module (to build one)

1 double-sided, plated-through PCB coded 01107021, 402 x 124mm – see bottom of page
2 200mm-wide heatsinks **[Altronics H0536]**
2 small PCB-mounting heatsinks **[Jaycar HH8516]**
12 TOP-3 silicone insulating washers
3 TO-220 silicone insulating washers
2 insulating bushes for the TO-220 transistors
4 M205 fuse clips (for F1 and F2)
2 fast-blow ceramic M205 fuses (5A for 8Ω load, 10A for 4Ω load) (F1, F2)
1 ferrite bead (FB1) **[Jaycar LF1250, Altronics L5250A]**
1 6-way PCB-mount screw terminal with barriers (CON2) **[Altronics P2106]**
1 2-way pluggable vertical terminal socket (CON3) **[Altronics P2572, Jaycar HM3112]**
1 2-way pluggable screw terminal (CON3) **[Altronics P2512, Jaycar HM3122]**
1 vertical PCB mount RCA (phono) socket (CON1) **[Altronics P0131]**
1 pot core bobbin for L1 **[Altronics L5305, Jaycar LF1062]**
1 2m length of 1.25mm enamelled copper wire (for winding L1)
1 60mm length of 0.7mm diameter tinned copper wire (links)
12 M3 x 20mm panhead machine screws
5 M3 x 15mm panhead machine screws
6 M3 x 6mm panhead machine screws
17 M3 hex nuts
12 M3 steel washers
6 M3 tapped 9mm spacers
2 transistor clamps **[Altronics H7300, Jaycar HH8600]**
1 15mm length of 25mm diameter heatshrink tubing (for L1)
1 60mm length of 1mm heatshrink tubing (for the wire links)
1 small tube of heatsink compound/thermal paste

Semiconductors
6 MJW21196 250V 16A NPN transistors (Q13-Q18) **[element14 1700966]** •
6 MJW21195 250V,16A PNP transistors (Q19-Q24) **[RS 790-5410]** •
1 MJE15035G 350V 4A PNP transistor (Q11) **[Mouser 863-MJE15035G]** •
1 MJE15034G 350V 4A NPN transistor (Q12) **[Mouser 863-MJE15034G]** •
1 FZT558TA 400V 300mA PNP transistor (Q7) **[RS 669-7388P]** •
1 FZT458TA 400V 300mA NPN transistor (Q9) **[RS 669-7326]** •
2 2SA1312 120V 100mA low-noise PNP transistors (Q1,Q2) •
3 BC546 65V 100mA NPN transistors (Q3, Q4, Q25)
1 BC639 80V 500mA NPN transistor (Q8)
3 BC556 65V 100mA PNP transistors (Q5, Q6, Q26)
1 BD139 80V 1.5A NPN transistor (Q10)
2 1N4148 75V 200mA signal diodes (D1, D2)
4 UF4003 200V 1A ultra-fast switching diodes• (D4-D7)
1 BAV21 250V 250mA low-capacitance switching diode• (D3) **[RS 436-7846]**
2 TL431 programmable voltage references, TO-92 (REF1, REF2) **[element14 3009364]** •
1 5mm green LED (LED1)
2 5mm red LEDs (LED2, LED3)

Capacitors
1 2200µF 16V or low-ESR 10V electrolytic
3 470µF 100V electrolytic **[element14 3464457]**
1 47µF non-polarised (NP/BP) electrolytic
1 47µF 50V electrolytic
1 47µF 16V electrolytic
1 1µF 100V MKT polyester
1 470nF 100V MKT polyester
2 100nF 100V MKT polyester
1 100nF 250V AC metallised polypropylene X2-class
2 10nF 100V MKT polyester
1 4.7nF MKT polyester
1 1nF 100V MKT polyester
1 75pF 200V COG **[Mouser 80-C315C750JCG or 80-C325C750KAG5TA]** •

Resistors *(all ¼W, 1% thin film unless specified)*
1 1MΩ
2 35.7kΩ • (or 2 82kΩ and 2 62kΩ)
1 33kΩ
2 33kΩ 1W 5% (carbon type OK)
1 22kΩ
2 18kΩ
5 10kΩ
1 10kΩ 1W 1% thin film **[Yageo MFR1WSFTE52-10K]** •
2 8.2kΩ
2 4.7kΩ
14 3.3kΩ
3 2.2kΩ
2 470Ω
2 220Ω
2 205Ω • (or 2 430Ω and 2 390Ω)
3 100Ω
1 100Ω 1W 5% (carbon type OK)
2 68Ω
2 68Ω 5W 5% wirewound (for testing purposes)
8 56Ω 1W 5% (carbon type OK)
2 47Ω
1 39Ω
1 22Ω
1 10Ω
12 0.47Ω 5W 5% wirewound
1 100Ω single-turn top-adjust trimpot (VR1) **[Altronics R2591]**
1 200Ω multi-turn top-adjust trimpot (VR2) **[Altronics R2372A]**

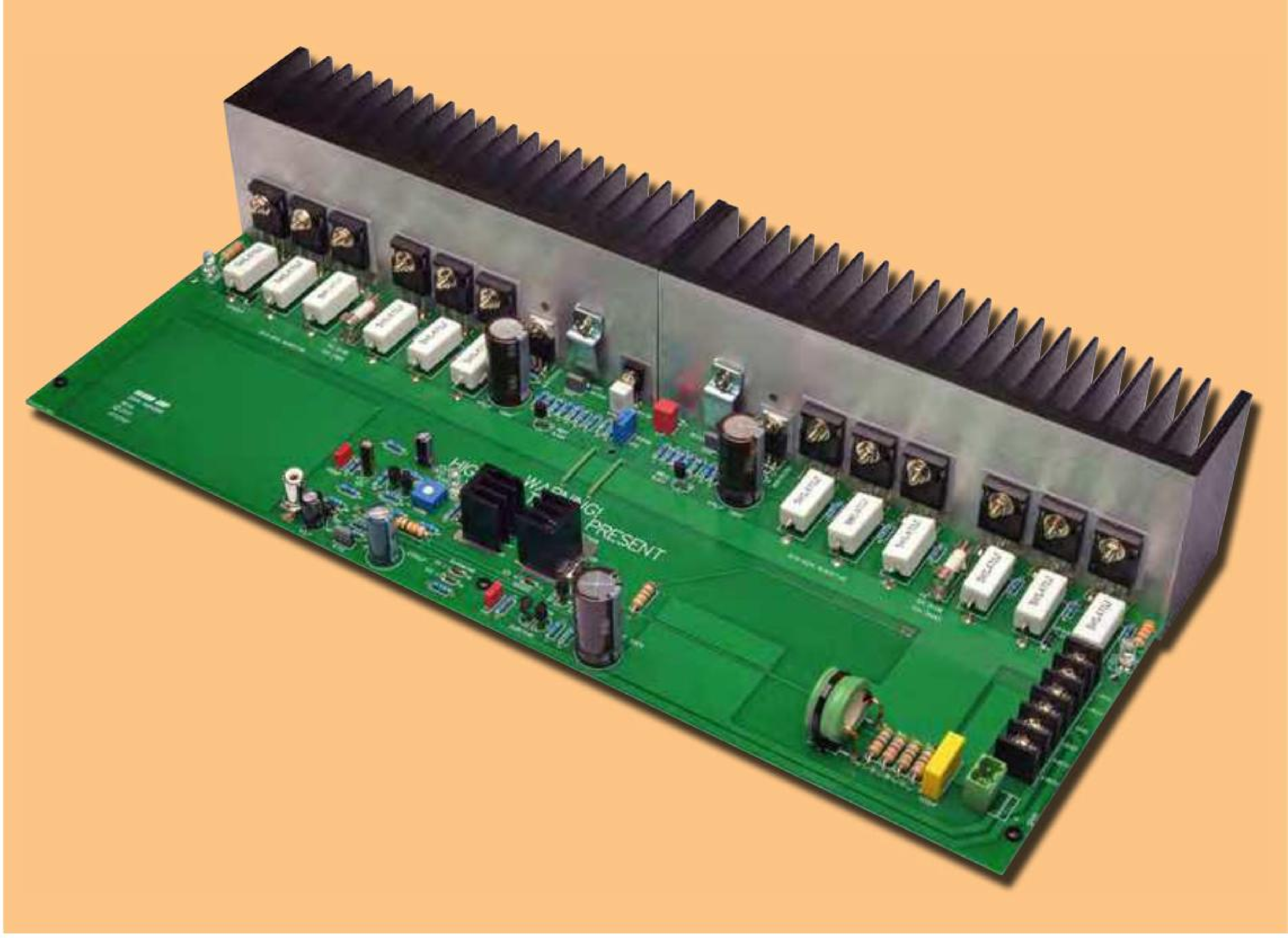
The parts list for the power supply, chassis, wiring etc will be presented in an upcoming issue.

UK readers – kit of parts for the 500W Power Amplifier

This is a large project with hard-to-find parts, especially the transistors. We normally supply the PCB and then readers source components using the Parts List. However, for this project constructors should buy kit SC6727 from Silicon Chip in Australia: **www.siliconchip.com.au/Shop/20/6727**

The UK's 2021 VAT/import regulations mean it is not worthwhile for Silicon Chip to sell to UK customers for purchases under AUD250 (plus p&p), but the size of this project means this restriction does not apply. **Note: UK purchasers will be liable for import duty and VAT.**

The parts supplied in the kit are detailed on the Silicon Chip website and include: the 500W amplifier module PCB; set of hard-to-get parts for the 500W amplifier module, including most of the semiconductors (marked with red dot above); Clipping Indicator PCB; Fan Controller/Speaker Protector PCB with programmed microcontroller, plus three 4-pin PWM fan headers.



The first part of our 500W Amplifier series focuses on describing how the Amplifier Module works; assembly and testing will be handled in later parts.

voltage clipping as clean and fast as that from positive voltage clipping, improving signal symmetry and reducing ringing under these conditions. For this role, we are using a BAV21 diode with a low capacitance of 2pF at 1MHz so that it doesn't affect sound quality.

Feedback and compensation

As mentioned, the feedback components at the base of Q2 set the closed-loop gain of the amplifier. The bottom end of the feedback network is connected to ground via a 2200µF electrolytic capacitor. As this reduces DC gain to unity, the amplifier output offset voltage is dramatically lower than it would otherwise be (by a factor of 38 times).

The 75pF compensation capacitor connected between the collector of Q9 and the base of Q8 prevents oscillation by limiting the slew rate.

The 22kΩ resistor in Q8's collector limits the current through Q9 under fault conditions. Should the amplifier output be shorted, it will try to pull the output either up or down as hard as possible, depending on the output offset voltage polarity.

If it tries to pull it up, the output current is inherently limited by the 15mA current source driving Q9 from Q7. However, if it tries to pull down, Q9 is capable of sinking much more current. The 22kΩ resistor limits Q9's base current and therefore, its collector current and dissipation. The 1nF parallel capacitor is required to keep its AC collector impedance low, improving stability.

Driver stage

The output signal from the voltage amplifier stage Q9 is coupled to driver transistors Q11 and Q12 via 47Ω resistors. The 47Ω resistors act as stoppers to help prevent parasitic oscillation in the output stage. They are also needed to allow the load line protection circuitry to override the drive from the VAS.

Q10 sets the DC voltage between Q7 and Q9, and this determines the quiescent current and power in the output stages. It provides a bias of about 2.3V or so between the bases of Q7 and Q9 so that they are always slightly conducting, even without an input signal.

Q10 is a 'V_{BE} multiplier', multiplying the voltage between its base and emitter by the ratio of its collector-emitter and base-emitter resistances. While trimpot VR2 varies the resulting collector-emitter voltage, it is actually adjusted to set the quiescent current through the output transistors.

It is important that the bias voltage produced by Q10 changes with the temperature of the output stage transistors. As the output transistors become hotter and their base-emitter voltages reduce, Q10's collector-emitter voltage should also drop, so that the quiescent current is the same or less as at lower temperatures, averting the danger of thermal runaway.

Output stage

The amplifier's output stage is effectively a complementary symmetry emitter follower comprising six NPN transistors (Q13-18) and six PNP transistors (Q19-Q24).

Each output power transistor has a 0.47Ω emitter resistor, and this more-or-less forces the output transistors to share the load current equally. The emitter resistors also help to stabilise the quiescent current to a small degree, and they slightly improve the frequency response of the output stage by providing current feedback.

Output offset adjustment

DC offset adjustment is provided by the 100Ω trimpot (VR1) between the emitters of the input pair, Q1 and Q2. VR1 adjusts the current balance between the input pair, and this causes the DC offset at the output to vary. The trimpot is set to make the DC offset as close to 0V as possible; it should be possible to keep this within ±5mV.

This is generally a good figure to keep low, but it's especially critical if using the amplifier to drive a step-up transformer for 100V line operation. That's because the DC resistance of the transformer primary is much lower than that of a loudspeaker voice coil, so significant DC can otherwise flow through it.

Load line protection

It is crucial to prevent the output transistors from operating beyond their Safe Operating Area (SOA). A high-power amplifier like this is quite likely to see abuse, being driven beyond its limits at times.

Fig.5 shows plots of collector current versus collector-emitter voltage (V_{CE}) for the six-per-side paralleled MJW21196 and MJW21195 output transistors. Of the two types, the MJW21195 (PNP) has the lower SOA curve, with a lower current allowed beyond 150V than the complementary MJW21196, so that is the curve we've plotted (the solid green line).

The SOA curve is based on a transistor junction temperature of 150°C and a case temperature of 25°C. That is not a very practical case temperature to maintain, especially when the transistors are dissipating significant power.

The actual transistor case temperature depends on the dissipation, the thermal resistance of each transistor's junction to its case (0.7°C/W) and the case-to-ambient thermal resistance, which is determined by the heatsink and fans. Having a large heatsink with fan-forced air greatly helps to keep transistor temperatures low.

At elevated temperatures, it is essential to ensure the transistors are not operated beyond their maximum power rating, 200W at 25°C, reducing by 1.43W per °C. This power rating curve can further reduce the power they can handle beyond that imposed by the SOA secondary breakdown area.

We plotted both the 25°C case temperature power curve (green curve) and the 50°C case temperature power curve (mauve curve). While a total of

1200W is available with the six 200W transistors at 25°C, only 985W is allowable with a 50°C case temperature.

The curves assume that each of the six parallel transistors share the current equally, a fair assumption since each has a relatively high-value emitter resistor. If one of the power transistors tends to take more than its share of load current, the voltage drop across its emitter resistor will be proportionately higher. This will throttle the transistor back until its current comes back into line with the others.

The blue and red curves show resistive 8Ω and 4Ω loads (straight lines) that assume the load is purely resistive. In practice, this is not true for loudspeakers as there is a considerable reactive impedance in a practical loudspeaker that causes its resistance to vary with frequency.

The curved blue and red lines show the load impedance curves assuming that the resistive and reactive impedances are equal. The plots show the worst-case impedance that occurs over the operating frequency range.

For example, for a 4Ω speaker, we plot the curve with a 2.83Ω resistance and 2.83Ω reactive impedance that's 90° out of phase with it ('j' is like 'i' in mathematics, the imaginary unit of value $\sqrt{-1}$, forming a complex impedance value).

WARNING!
HIGH V GE ESENT

A close-up of the front-end circuitry of the 500W Amplifier Module.

Calculation of the total impedance can be visualised as the two impedances forming two sides of a right-angle triangle with the hypotenuse length equalling the total, which in this case is either 4Ω or 8Ω.

These plots are for a rather severe amplifier load. Typically, a loudspeaker will not exhibit such a load, but we want to ensure the amplifier will not be damaged by designing for worst-case loads.

Note how the curved impedance plots encroach quite a bit closer to the SOA curve than the purely resistive loads. Note also that at elevated temperatures, the allowable dissipation curve comes close to the 4Ω reactive impedance plot, especially around the 60V to 100V V_{CE} region. At case temperatures above 50°C, the allowable transistor dissipation could possibly be exceeded.

The two protection lines on the graph prevent this. The dashed green line is for a transistor case temperature of 25°C, while the dashed mauve line is for a 50°C case temperature. The lines show the points on the graph where the output transistors are protected by reducing their base drive should the load reach the protection line.

The protection lines shift closer to the 4Ω impedance curve with increasing temperature. Also, the protection lines have a dual slope with one straight line between the Y-axis and the small circle (dot), and the second line between that dot and the X-axis. Note that where the line meets the X-axis, it must be at least the total supply voltage (160V) to prevent spurious limiting near zero output current.

As the temperature rises, the voltage at the zero current axis reduces. However, even the 50°C curve meets the axis above 160V, at 165V. If the amplifier gets significantly hotter, perhaps beyond 60°C, the output will probably get cut off, but maybe that is not a bad thing, as it's a sign that the cooling system might have failed.

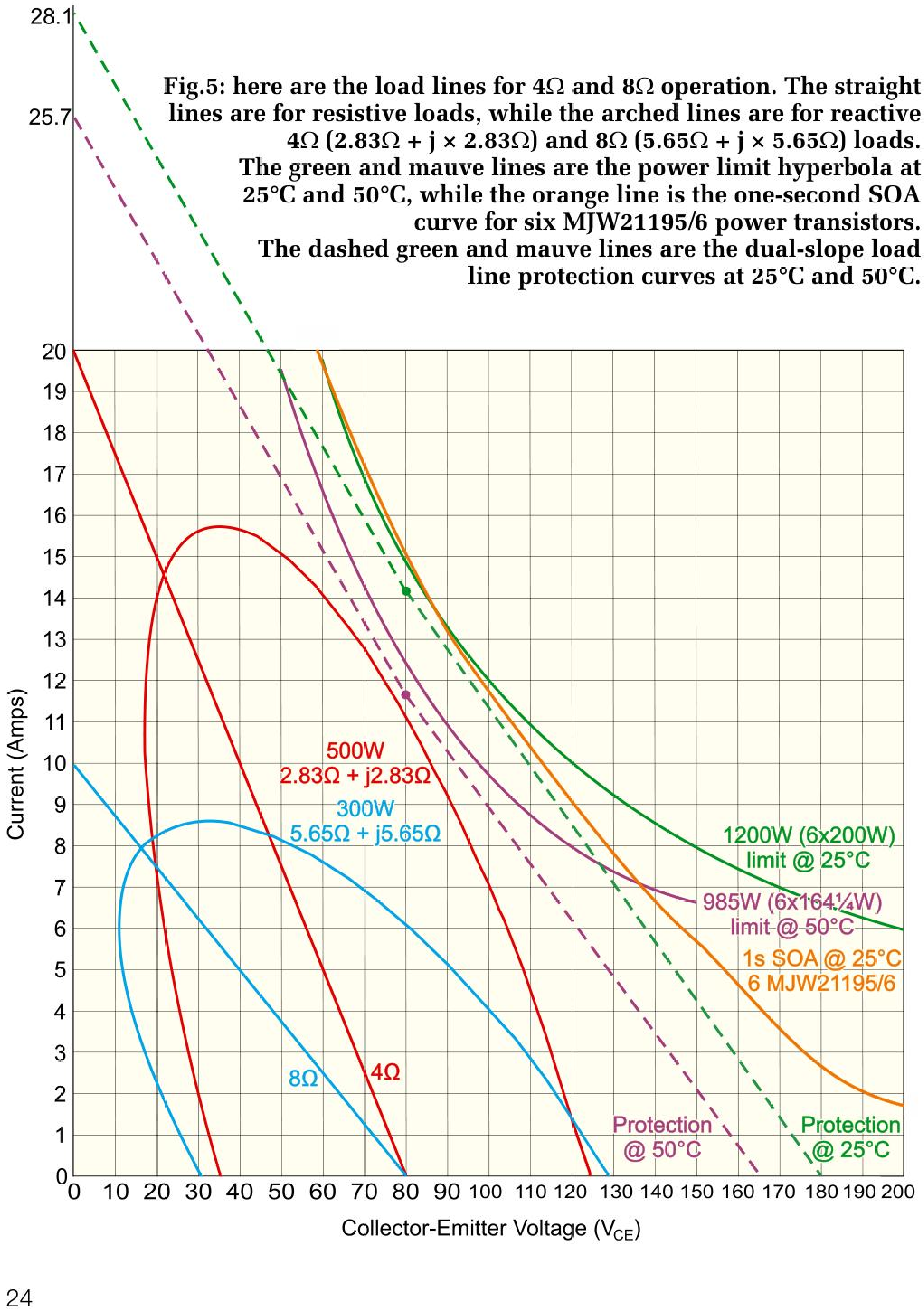


Fig.5: here are the load lines for 4Ω and 8Ω operation. The straight lines are for resistive loads, while the arched lines are for reactive 4Ω (2.83Ω + j × 2.83Ω) and 8Ω (5.65Ω + j × 5.65Ω) loads. The green and mauve lines are the power limit hyperbola at 25°C and 50°C, while the orange line is the one-second SOA curve for six MJW21195/6 power transistors. The dashed green and mauve lines are the dual-slope load line protection curves at 25°C and 50°C.

While the difference between the two slopes in the protection curve is subtle, this is necessary to more closely follow the power rating curve and hence prevent the protection curve at 50°C and beyond from encroaching on the 4Ω impedance curve at a V_{CE} of around 70V.

SOA protection circuitry

This dual-slope foldback protection scheme is based on the research paper titled, *The Safe Operating Area (SOA) Protection of Linear Audio Power Amplifiers* by Michael Kiwanuka, BSc (Hons) Electronic Engineering, which you can view at: **https://bit.ly/pe-apr23-soa**

The supply voltage, output voltage and current through the output transistors are all monitored to provide load-line protection over the entire voltage and current ranges of the amplifier.

Transistors Q25 and Q26 and diodes D6 and D7 provide the protection feature. Q25 (NPN) can shut off the MJW21196 transistors, while Q26 (PNP) acts on the MJW21195 transistors. The diodes are included to prevent Q25 and Q26 from shunting the drive signal when they are reverse-biased. This happens for every half-cycle of the signal to the driver transistors.

The circuits around Q25 and Q26 are essentially identical.

Normally, Q25 and Q26 are biased off and play no part in the amplifier's operation. However, if the load encroaches upon the protection curve, Q25 and/or Q26 switch on to throttle back drive to the output transistors, limiting the output current and protecting the transistors. This also protects against short circuits.

Transistor Q25 and Q26 are mounted on the amplifier's heatsink so that the protection circuit curves shift with temperature as required.

In more detail, the voltage across each 0.47Ω output stage emitter resistor is monitored via a set of 3.3kΩ resistors. These voltages are averaged (equivalent to being summed) at the base of Q25 or Q26. Resistive dividers formed from pairs of paralleled resistors provide output voltage and supply voltage monitoring by feeding extra current into these summing points.

Effectively, what these dividers do is make it so that as the voltage across a set of output resistors reduces (either due to reduced supply voltage, or the output swinging closer to that rail), the protection circuitry becomes more insensitive and requires a higher output current to be triggered. Similarly, as the V_{CE} increases, the trip current decreases, forming the 'curves' shown in Fig.5.

The finished case is simple, with only a power button and clipping indicator LED on the front and audio input/output and power socket on the back.

The dual slope in the protection circuit is created by voltage reference REF1 for the positive half of the circuit and REF2 for the negative half. The bias current to operate these devices comes via 18kΩ series resistors. REF1 and REF2 are adjustable voltage references, with the 10kΩ and 3.3kΩ resistors setting the voltage across them to 10V.

The protection circuit relies on the base-emitter voltage of Q25/Q26 being around 0.6V at 25°C. This voltage drops to 0.55V at 50°C, so these transistors switch on with less applied voltage at higher temperatures. This shifts the protection line downwards with elevated temperature, following the downward movement of the output transistors' power rating curve.

Diodes D4 and D5 between the amplifier output and supply rails are also part of the protection circuitry. They absorb any large spikes generated by the loudspeaker's inductance when the protection circuit cuts the drive to the output transistors. D4 and D5 are fast recovery diodes, included to ensure their operation at high frequencies and high power.

These diodes are even more critical if driving a line transformer as its primary inductance is likely to be significantly higher than any loudspeaker load.

Output RLC filter

The remaining circuit feature is the output RLC (resistor-inductor-capacitor) filter, comprising a 2.2µH air-cored choke, eight paralleled 56Ω resistors (giving 7Ω) and a 100nF capacitor. This output filter effectively isolates the amplifier from any large capacitive reactance in the load, thereby ensuring unconditional stability.

It also helps attenuate any RF signals picked up by the loudspeaker leads and stops them from being fed back to the early stages of the amplifier, where they could cause RF breakthrough.

Fuse protection

The output stage supply rails are fed via fuses F1 and F2 from the +80V and –80V main power supply rails. These provide 'last-ditch' protection to the amplifier, limiting the damage in the case of a severe fault. The recommended fuses are ceramic types. LED2 is a blown-fuse indicator for F1 and LED3 for F2. They light up if the fuse is blown as it isn't always obvious, especially with ceramic types.

Next month

The following article next month will have the full module construction details, including the heatsink drilling and instructions for winding inductor L1.

In the June issue, we'll show you how to build a suitable power supply, mount it and the *Amplifier Module* in the chassis, and wire it all up along with the *Fan Controller*, fans, *Speaker Protector* and *Clipping Indicator*.

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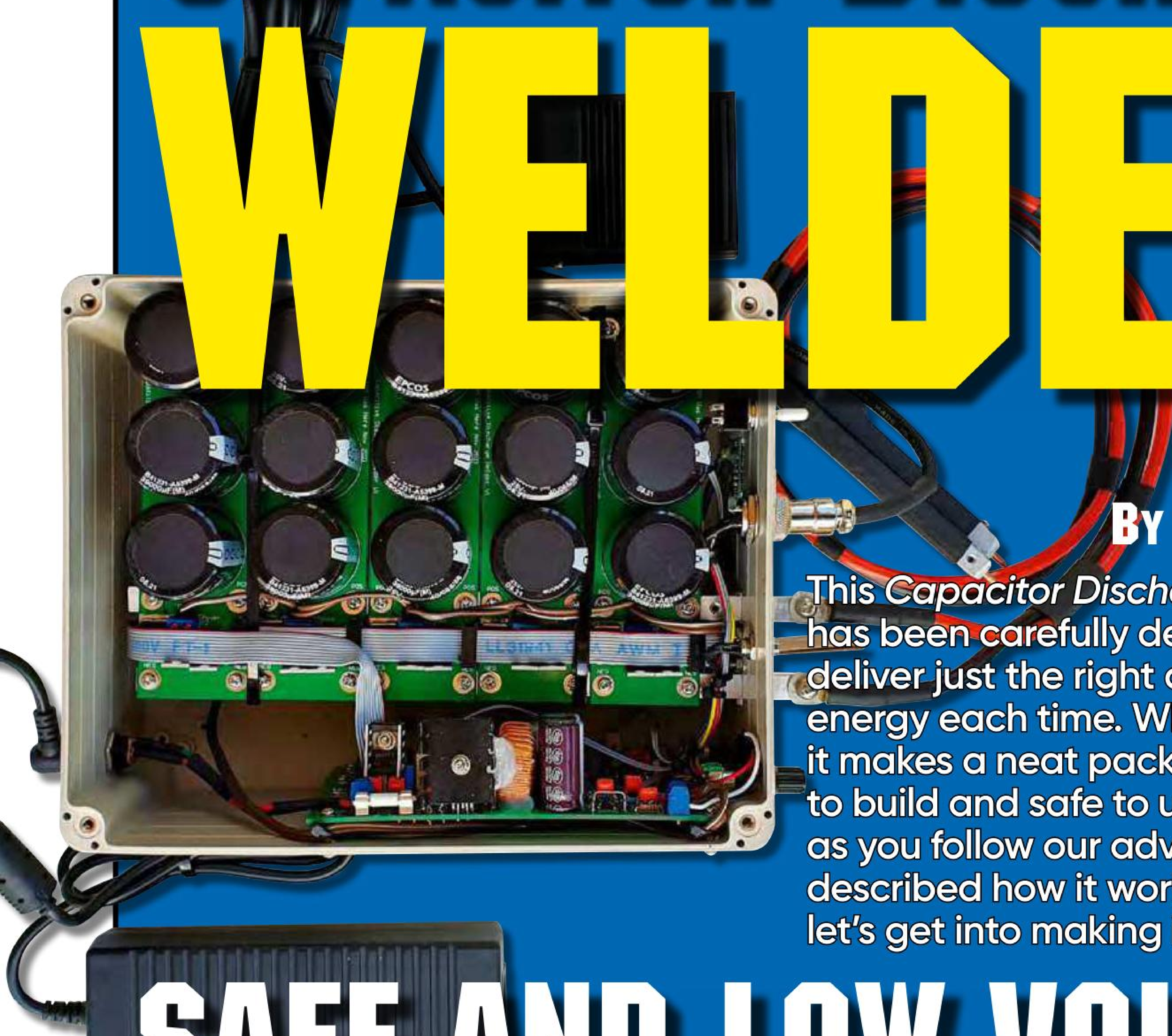
CAPACITOR DISCHARGE WELDER

PART 2

BY PHIL PROSSER



This *Capacitor Discharge Welder* has been carefully designed to deliver just the right amount of weld energy each time. When completed, it makes a neat package that's easy to build and safe to use, so long as you follow our advice. Having described how it works last month, let's get into making it.

SAFE AND LOW VOLTAGE

The Capacitor Discharge Welder comprises three main electronic modules: the Power Supply, which is responsible for charging the capacitors; the Controller Module, which determines when voltage is applied across the welding tips; and an Energy Storage Module bank, typically made from around 10 modules joined to a common pair of bus bars, that hold the storage capacitors and MOSFETs.

Because of this modular approach, not only can you scale the system to meet your needs, but the PCB cost is kept down, and assembly is relatively straightforward. You build and test the modules, assemble them into the case, make the welding tips and cables, and finally wire it all up.

Construction

The first step in building the CD Welder is to assemble one Power Supply Module, one Controller Module and several Energy Storage Modules (ESMs). Each is built on a different PCB, but all the PCBs are the same size at 150 x 42.5mm.

We'll start with the Power Supply Module. Its PCB is coded 29103221 and Fig.6 is its overlay diagram, which shows the parts' location mount on the board.

Start by soldering the sole SMD ceramic capacitor (100nF) near the MC34167 regulator IC. Next, mount the

Safety warning

Capacitor Discharge Welding works by generating extremely high current pulses, and consequently, strong magnetic fields. Do not build or use this project if you have a pacemaker or similar sensitive device.

This device can generate sparks and heat. Users must wear appropriate personal protective equipment such as AS/NZS 1337.1, DIN 169 Shade 3 welding glasses. These provide mechanical and IR/UV protection.

INA282 current sense amplifier, which comes in an SMD package (SOIC). Watch its orientation; make sure its pin 1 is facing as shown before soldering its pins and then check for bridges.

Follow with all the resistors and diodes (except for diode D1) with the diode cathode stripes facing as shown, leaving the taller shunt resistor until last. There are three different diode types used: 1N4148, 1N4004 and zener, so don't get them mixed up.

Pay attention to the two different resistor value options shown in Fig.6. If you are using a DC power supply that can deliver at least 5A, you can use the values shown for 5A charging. Otherwise, stick with 2A charging.

Now install the sole transistor, facing as shown, then all the capacitors. Many of the latter are not polarised, but for those which are polarised (the electrolytics), these all have the longer positive leads going to pads on the right-hand side. Note that while you could use 100nF MKT capacitors, multi-layer ceramics will also work.

Next come the connectors. There are two screw terminals, a polarised header for the Charge LED and a 2x5 pin header to connect to the other modules. Make sure the screw terminal wire entries face the outside of the board as shown.

Mount the 6TQ045-M3 diode (D1) close to the board by pushing it down fully before soldering and trimming its leads. Also install the fuse clips (with the tabs towards the outside) and fuse, the LM358 op amp and 10kΩ linear voltage control potentiometer.

Now fit the LM7815 regulator and attach a small flag heatsink using a machine screw, shakeproof washer and nut as it gets warm during operation.

Mount the 220µH toroidal inductor on the board, then finally the MC34167 switch-mode regulator. This also requires a small heatsink such as Altronics H0625 with an insulating bush and silicone pad. Hold this all together using an M3 machine screw, star washer and nut in the usual manner.

Charge
Foot Switch
Volts
SAFE
Volts

The CD Welder fully assembled and ready to be used in anger (or calmly, it's up to you).

Control board

The Controller PCB is coded 29103222 – refer to Fig.7.

Start by installing all the resistors and diodes, checking that the diodes are the right way around, then follow with the four NE555 timer chips, with their pin 1 notches/dots to the left.

Next, fit all the ceramic MKT and electrolytic capacitors. Note the two different types of 1µF capacitor as well as different types of 220nF capacitors. The electrolytics have longer leads for their positive connections, and these go to the side marked + on the overlay.

Now mount the small transistor, facing as shown, followed by the 100kΩ linear potentiometer and the 2-way and 10-way headers.

If you want to make the controller switchable for two pulses, make a cable with a switch at one end and a header plug on the other so that it can plug into CON8. Alternatively, you could install a jumper on CON8 and fix this setting, as we did.

Energy Storage Modules

The ESM boards are coded 29103223, and the components are mounted as shown in Fig.8 and Fig.9. Presumably by now you will have figured out how many you need to build and obtained the appropriate capacitors. Generally, there are three caps per board, but some of the recommended configurations use two. In this case, fit the two closest to the headers.

Start by fitting the surface-mount resistors and capacitors on the underside of the PCB. Make sure the 100nF capacitors are mounted either side of the MOSFET driver (IC8). Then solder that driver IC, being careful not to short

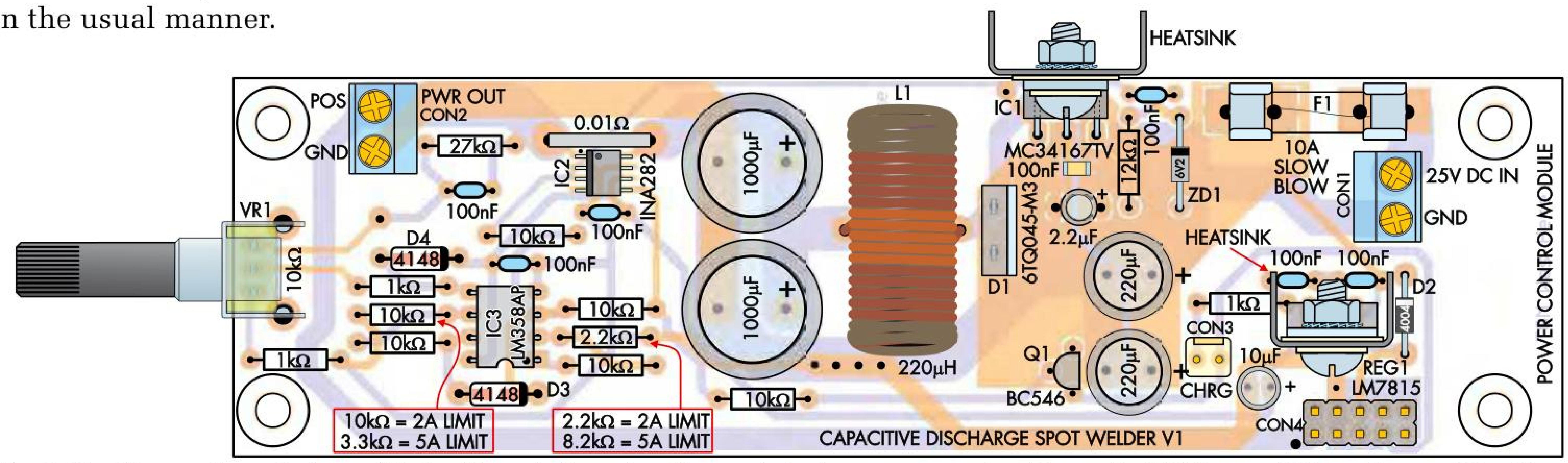

HEATSINK
L1
IC1
POS
PWR OUT
CON2
GND
0.01Ω
27kΩ
IC2
INA282
1000µF
100nF
VR1
10kΩ
D4
4148
10kΩ
100nF
100nF
1kΩ
10kΩ
10kΩ
1kΩ
IC3
LM358AP
10kΩ
2.2kΩ
10kΩ
4148
D3
10kΩ
10kΩ = 2A LIMIT
3.3kΩ = 5A LIMIT
2.2kΩ = 2A LIMIT
8.2kΩ = 5A LIMIT
1000µF
220µH
MC34167TV
100nF
12kΩ
100nF
6V2
ZD1
6TQ045-M3
D1
2.2µF
220µF
220µF
Q1
BC546
F1
10A
SLOW
BLOW
CON1
25V DC IN
GND
HEATSINK
100nF
100nF
D2
4004
1kΩ
CON3
CHRG
10µF
REG1
LM7815
CON4
POWER CONTROL MODULE
CAPACITIVE DISCHARGE SPOT WELDER V1

Fig.6: the Power Supply board is built mainly using through-hole components. The only SMDs are IC2 and one 100nF capacitor near IC1, so fit those first. Watch the orientations of IC2, IC3, the diodes, electrolytic capacitors, REG1 and the terminal blocks.

any leads (you can clean up any bridges using flux paste and solder wick).

Next, mount the RFN20NS flyback diode (D9) to the PCB. It's easier if you spread a thin layer of flux paste on all its pads first. You will want to get a good lot of heat into the PCB; start by tacking down the two anode leads, then solder the main body of the diode. This will not dissipate much power, but you want a good solder joint here.

Then fit the two MOSFETs, keeping their leads short. Their metal tabs face away from the capacitors, and their source and drain pins connect to copper fills. These junctions will see very high current pulses, so be sure to get these properly hot when soldering to form nice-looking fillets.

Now mount the 2x5 control header, the terminal block and finally, the capacitors. Make sure their positive sides go in the direction indicated, and the negative side stripes face away from this. (Reversed capacitors will likely lead to an earth-shattering kaboom!)

Repeat the ESM assembly until you have enough of these modules, and are ready to test them and then proceed to final assembly.

Testing

Start by testing the modules individually, beginning with the Power Supply Module. To start with, solder the leads of one LED to a length of light-duty twin-lead cable (eg, two wires stripped from ribbon cable) and solder/crimp the other end into a pluggable header, and connect this to CON3, the charge LED header. Make sure the anode (longer LED lead) goes to pin 1.

Connect the Power Supply board to a DC voltage source of at least 25V – up to 35V is acceptable. Make sure you have set the current limit (2A or 5A) to match your supply. Set your DVM to a DC volts range and put a 5W 82Ω resistor across CON2, 'Power Output'. Apply power and check the following:

- The output of the LM7815 is 15V ±0.25V. Its output is accessible on pin 2 of CON4, the control header. If not, check that it is the right way around and there are no shorts.
- Check pin 1 of CON2, the 'Power Out' connector, is between 2V and 25V. Also check that this can be controlled using potentiometer VR1. If this is not working, check the following:
- Check the INA282 (IC2) is in the right way around.
- Verify that the 82Ω test resistor is connected correctly (eg, measure the resistance across the terminals of CON2).
- Check the MC34167 is oscillating; there will be a 72kHz signal at pin 2.
- Check D1 is in the right way around.
- Check that the feedback pin 1 of the MC34167 has about 5.05V on it. If not, verify that the LM358 op amp is operating properly. Check the voltages at its power and ground pins (pins 8 and 1, respectively), and verify that the voltage at input pin 5 is an appropriate fraction of the output voltage, and that pin 7 is an amplified version of this. Check that diodes D4 and D5 are in the right way around.
- Assuming that's working, put an ammeter on its 10A range across the terminals of CON2 and check that the current is close to the expected 2A or 5A. If not, look for problems near the INA282 (IC2).

Testing the Controller

To test the controller, ideally, you will need an oscilloscope. Make a 10-way IDC lead to connect the Power Supply module to the Controller module, ensuring that pin 1 connects to pin 1. Apply power and check the following:

- Each NE555 chip has 15V at its pin 8.
- The base of transistor Q1 is pulled up to within 0.6V of the 15V rail, turning it off.
- The TRIGGER output of IC6 (pin 3) is close to 0V

The next part is easiest if you assemble the foot pedal trigger by extending the existing lead with the two-metre length of microphone cable. You can simply snip off the screen wires as they are not required; just use the two internal conductors, then add liberal layers of heatshrink to protect the junction.

Now temporarily soldering a length of light-duty twin lead to the other end (eg, stripped from spare ribbon cable) and solder/crimp this to a polarised header plug which connects to CON5.

Connect your oscilloscope to the output pins (pin 3) of IC4, IC5 and IC7. If you only have a single-channel or two-channel oscilloscope, start with IC4 and/or IC5 and then test the rest later.

Press the footswitch and check that IC4 generates a pulse of about 0.1ms and IC5 generates a pulse of about 5ms. Then check that IC7 generates a pulse length that is controllable using potentiometer VR2, from about 0.2ms to over 20ms.

Next, check that the trigger output on pin 9 of the 2x5 header (or pin 3 of IC7) contains one or two pulses as set by the switch/jumper on CON8.

If there are problems, check the power supply to the NE555 ICs; there should be 15V between pins 8 and 1 of each chip.

Verify that the trigger input (pin 2) is being pulled low on IC4, and that the inputs to subsequent NE555s have a short negative-going pulse (this is capacitively coupled, so look closely with the scope).

Check also that the diodes are in the right way around, that Q2 is indeed a PNP device and that the INHIBIT line is not pulled low by the Power Supply.

Make sure that you are happy with the operation of the power supply and controller modules before assembling the CD Welder.

Testing the ESMs

To check out each Energy Storage Module, connect one at a time to the Controller and Charger modules. Use medium-duty hookup wire (0.7mm diameter copper/21AWG) such as Altronics Cat W2261/W2260 or Jaycar Cat WH3045/WH3046 to connect the Power Out connector on the Power Supply board (CON2) to the Power In connector (CON10) on the Energy Store Module.

You'll also need a control ribbon cable with three 10-way IDC line sockets to connect the Power Supply, Controller board and ESM together.

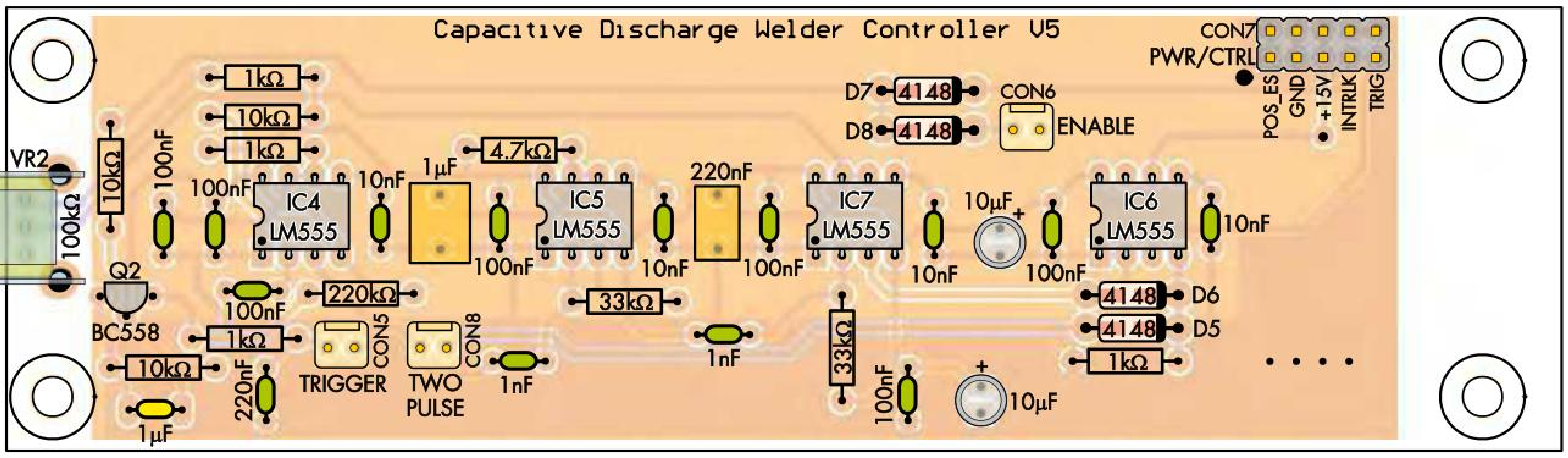
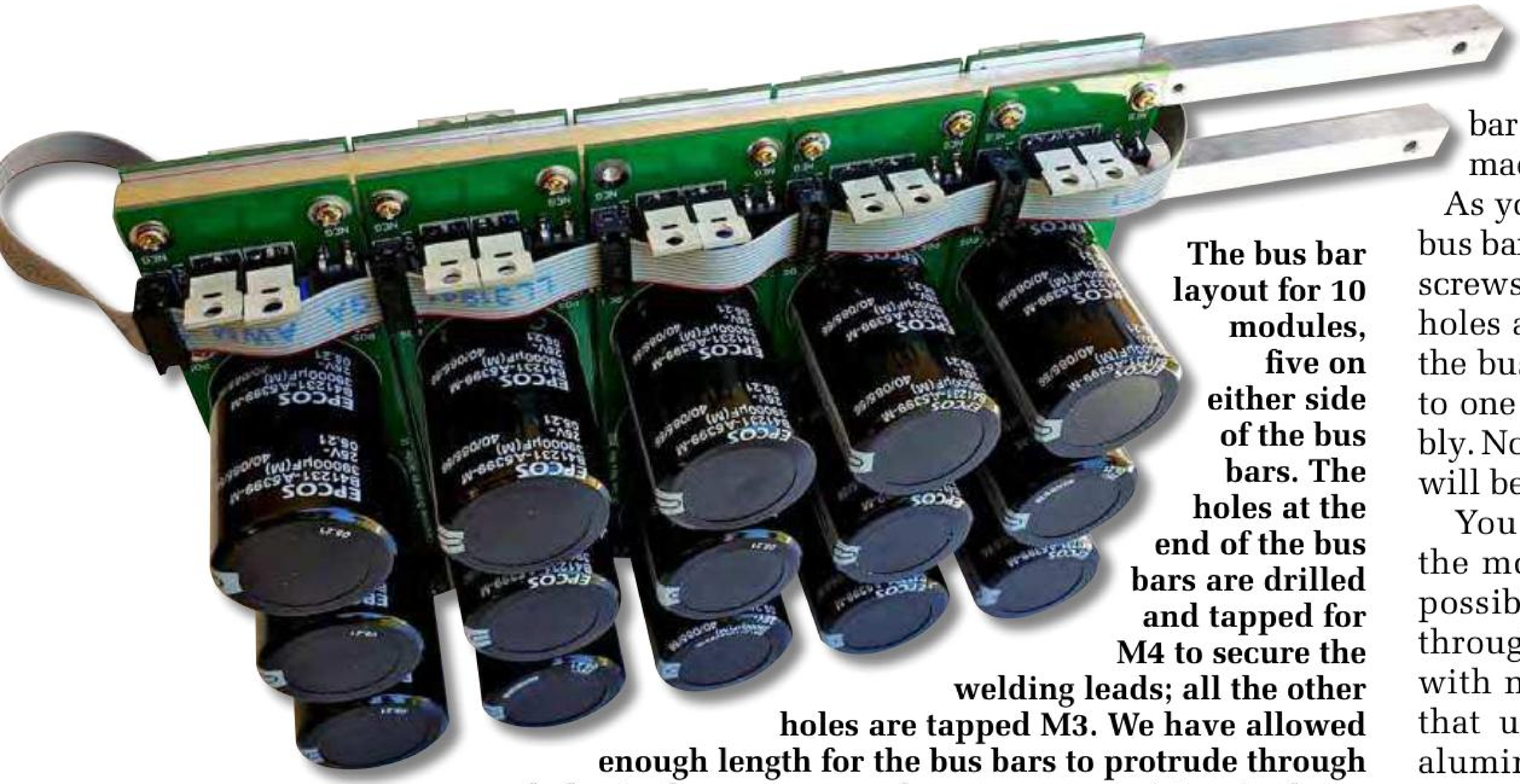


Fig.7: the Control board uses all through-hole parts and assembly is straightforward. Again, be careful to orient the diodes, electrolytic capacitors and ICs as shown.



The bus bar layout for 10 modules, five on either side of the bus bars. The holes at the end of the bus bars are drilled and tapped for M4 to secure the welding leads; all the other holes are tapped M3. We have allowed enough length for the bus bars to protrude through holes in the case, as we do not want any joints in these.

Connect an 82Ω 5W test resistor across the ESM output using 16mm M3 machine screws, nuts and washers. Apply power and check that the capacitors charge and that you can adjust the voltage using VR1.

The 'Output -VE' connection (right near the edge of the PCB) will be pulled up to the same voltage by that 82Ω resistor. Use an oscilloscope to watch the voltage on that pin and press the trigger. There is a convenient ground on the power header; we also added a ground via on the board between the capacitors.

After triggering, you should be able to see the output pulled to ground in two pulses (with dual pulse mode on). If this does not work, use the scope to check for the trigger pulses on the control cable, check the +15V rail and check that the TC1427 is sending pulses to the MOSFET gates. Check all cabling and the orientation of the components.

Now swap that 82Ω resistor for a 0.27Ω 5W resistor. Repeat the test, and check that everything works. At 25V, this will pass close to 100A.

You will see the Charge LED come on, especially with long pulse lengths and high voltages. You will also feel the 0.27Ω resistor get hot after several shots. This is normal. You may blow this resistor, so if things look odd, check it is still 0.27Ω.

Bus bars

Once you've tested the modules, it's time to put them all together.

We have laid these boards out such that they can mount back-to-back on two 260mm-long bus bars. Fig.11 shows where to drill holes to allow M3 screws to hold pairs of modules into common tapped holes.

Mount the modules to the bus bar using 6mm-long M3 panhead machine screws and star washers.

As you assemble the modules to the bus bars, put 10mm M3 spacers, 6mm screws and star washers between the holes at the far end of the PCBs from the bus bars, securing pairs of boards to one another, stabilising the assembly. Now tighten the screws well; these will be carrying a lot of current.

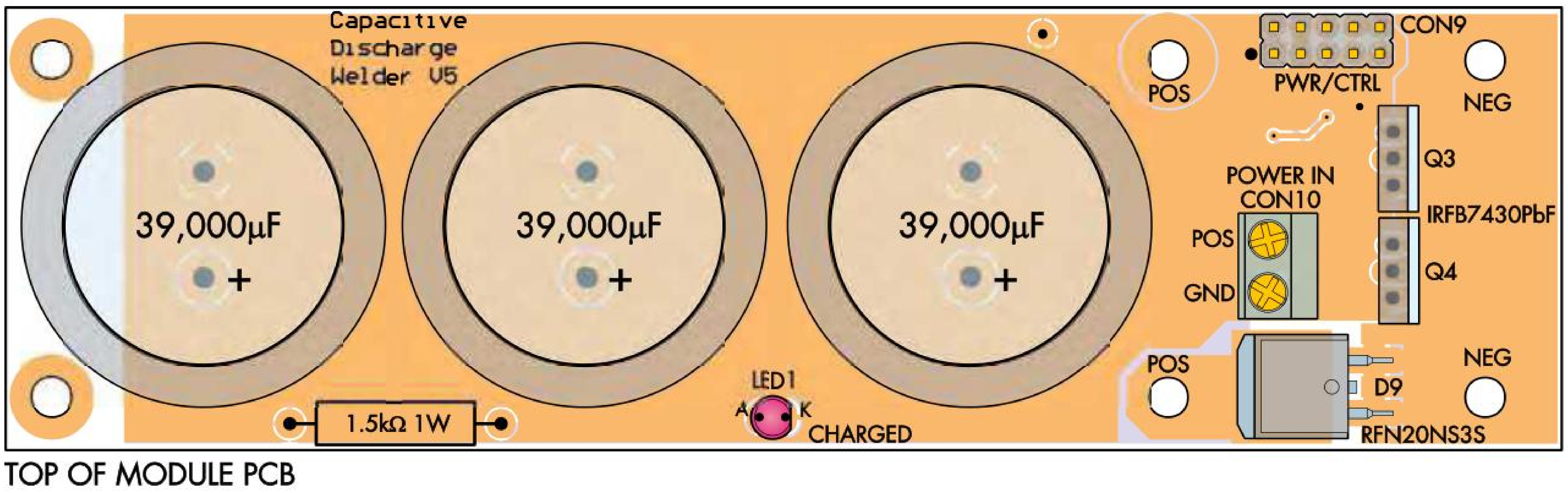
You may find another way to lay the modules out. While it might be possible to run machine screws right through holes drilled in the bus bars with nuts on the other side, we feel that using threaded holes into the aluminium is important to keep the resistance down. So we strongly advise you to take the time to tap all these holes (aluminium is soft, and you can use a through-tap, so it isn't that hard).

Cabling

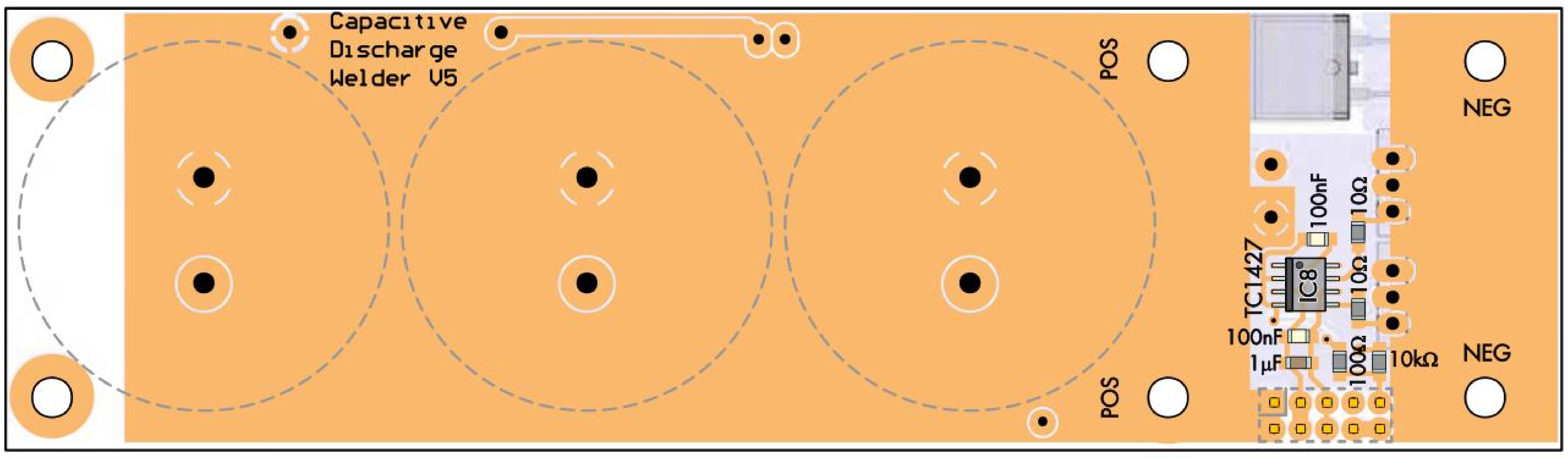
We have endeavoured to keep cabling as simple as possible. Fig.10 shows the complete layout. We extended the ribbon and power cable from the Energy Store Modules to the Charge and Control modules to suit our application. Try not to make these more than a few hundred millimetres long.

Fig.12 shows the layout we came up with to fit the modules inside the case and how most of the wiring is routed.

Note that it is necessary to cut the Inhibit line in the ribbon cable so that it only connects the Controller and Power Supply modules. This is to prevent it from acting as an antenna and picking up pulses during welding.



TOP OF MODULE PCB



UNDERSIDE OF MODULE PCB

Fig.8 and Fig.9: the ESM has parts on both sides, although the underside components are limited to a few SMDs near the MOSFETs; mainly, the driver IC and associated passives. Fit all those first, then flip the board over and solder the remaining components to the top side. Be very careful with the electrolytic capacitor and MOSFET orientations, as putting them in backwards would be disastrous.

You will need to make up a cable for the enable switch similar to the one you made before for the charge LED. This will plug into CON6 at one end and go to the terminals of a toggle switch at the other end.

Now would also be a good time to disconnect the twin lead from the microphone cable in the footswitch assembly you made earlier, and instead solder these to the microphone plug (footswitch end) and socket specified in the parts list last month.

In our application, we started with 300mm lengths of twin lead and trimmed them as required.

The power connection from the chassis DC socket to the Power Supply board needs to be made using 5A-rated cable; the type of wire used earlier to connect the Power Supply to the ESMs should be suitable.

While the ribbon cable connects the output of the Power Supply to each ESM, it is only rated at 1A per wire. Two wires are used for power, plus two for ground, limiting charging over the ribbon cable to 2A.

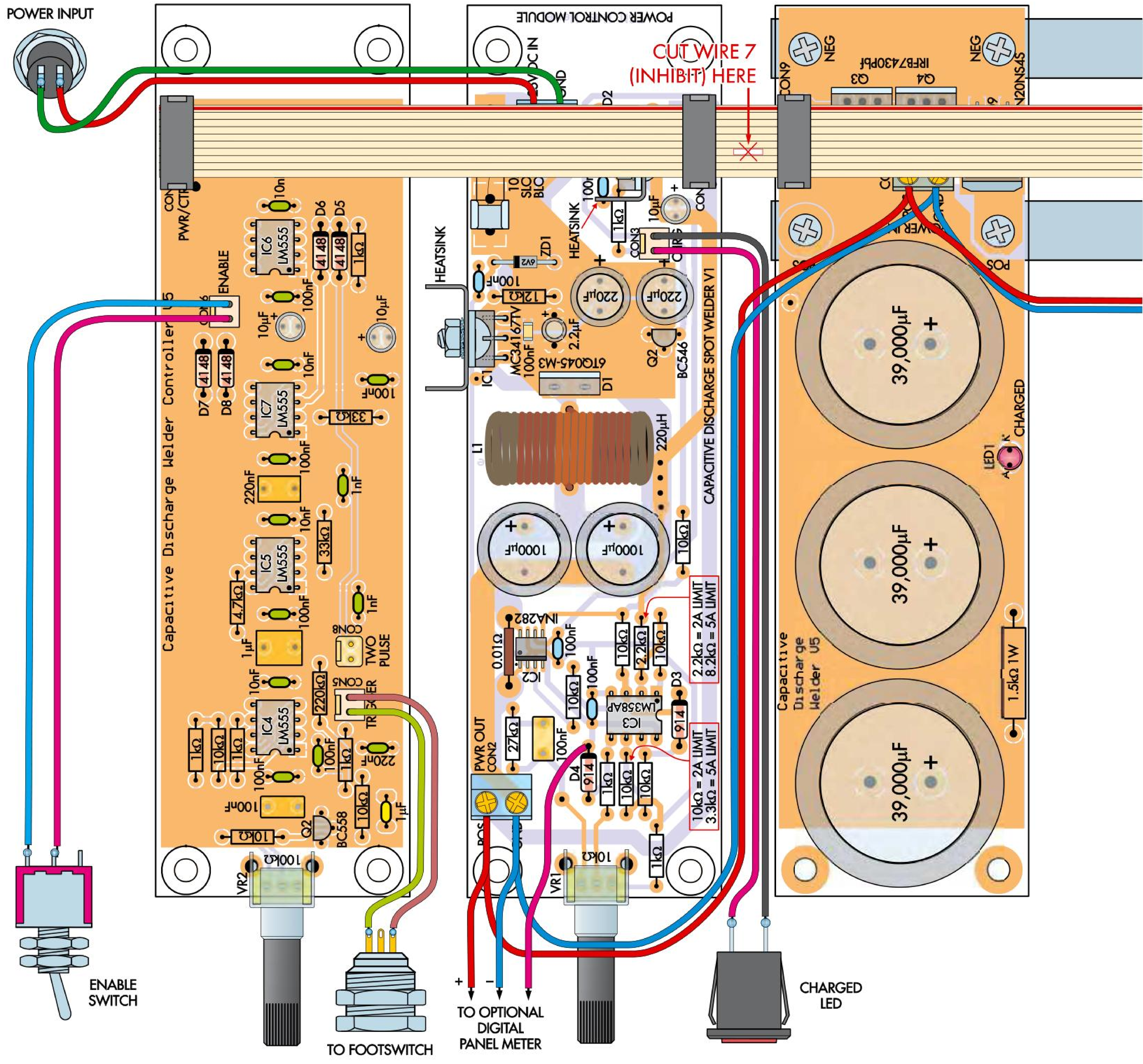
So if you want to charge at 5A, the IDC headers will 'need help'. This is the purpose of CON10 on each ESM. You will need to wire all those headers back to CON2 on the Power Supply using 5A-rated cable. We used Altronics Cat W2109 for this job. Don't use thicker wire if you can avoid it, as you need to fit two pairs into each terminal block to daisy-chain them.

For this, we cut nine 60mm lengths plus one long length, stripped and tinned these together and used a bit of heatshrink to make it look tidy. This is a little fiddly, but it is the best approach we could come up with that was not big or too expensive. By paralleling the ribbon cable, this heavy-duty wire will take the majority of current during charging.

Make sure you connect each terminal with the same polarity; otherwise, it will short out the Power Supply!

To make the ribbon cable that connects all the modules, assuming you have 10 ESMs, you need 12 10-way IDC line sockets and about 610mm of 10-way ribbon cable, depending on your layout. Fit the IDC connectors as shown in Fig.13.

We crimped the IDC connectors using a vice, although specific tools are also available to do this. If using a vice, add timber blocks or sheets on either side of the connectors to avoid marring them and make it less likely to break them when squeezed.


POWER INPUT
POWER CONTROL MODULE
CUT WIRE 7 (INHIBIT) HERE
Capacitive Discharge Welder Controller U5
ENABLE
PWR/CTRL
IC6 LM555
IC7 LM555
IC5 LM555
IC4 LM555
TWO PULSE
TRIGGER
Q2 BC558
VR2 100kΩ
HEATSINK
IC1 MC34167TV
6TQ045-M3
D1
ZD1
L1 220µH
1000µF
1000µF
220µF
220µF
Q2 BC546
CAPACITIVE DISCHARGE SPOT WELDER V1
INA282
IC2
0.01Ω
IC3 LM358AP
2.2kΩ = 2A LIMIT
8.2kΩ = 5A LIMIT
10kΩ = 2A LIMIT
3.3kΩ = 5A LIMIT
PWR OUT CON2
VR1 10kΩ
CON9
NEG
Q3
Q4
IRFB7430PbF
39,000µF
39,000µF
39,000µF
LED1
CHARGED
1.5kΩ 1W
Capacitive Discharge Welder U5
POS
ENABLE SWITCH
TO FOOTSWITCH
+
−
TO OPTIONAL DIGITAL PANEL METER
CHARGED LED

As mentioned earlier, we recommend cutting the inhibit line (wire 7) between the Power Supply Module and the Energy Store modules. Simply slit the ribbon cable on either side of wire 7 over a 10mm section and snip a 5mm section from it using side cutters. This reduces the chance of EMI pick-up.

Cables

The footswitch is our solution to keeping your hands free to weld, but you could place a button on one of the leads as an alternative if you wish. The recommended footswitch comes with a short lead, hence our earlier instructions to extend it with about two metres of microphone cable. Now that you've added the plug and socket, this cable should be complete.

For the all-important welding cables, we crimped Altronics H1757B non-insulated eyelet lugs at the Welder end (Jaycar PT4936 is equivalent). We were lucky and our crimping tool worked on these, but we know from experience that you can also solder them (with a powerful iron) or crimp them in a vice. We put 10mm heatshrink over the terminal to ensure nothing shorts to it.

We made the welding handles and tips as shown in Fig.14. These comprise a 100mm length of 10mm square aluminium bar with a 4mm hole drilled in the end to accept the welding cable. Two additional M4 threaded holes allow 6mm-long M4 screws to fix the welding cable.

After making them, we applied 13mm heatshrink tubing over the handles to make them easier to hold and act as strain relief for the cables.

At the welding tips, we have again drilled 3mm holes in the end of the handles and drilled and tapped an M3 threaded hole to hold the tip. We tried various copper welding tips and feel that 3mm rod filed to a point are pretty good.

We used small pieces of 20mm heatshrink to ensure the positive and negative welding cables remain close to one another along the bulk of their length. We do this to minimise the inductance in the welding cable loop. If there is a lot of inductance, then there will be so much energy stored in this that the MOSFETs have to switch, and the flyback diodes need to redirect.

Case assembly

There are many ways of packaging this up. By avoiding mains wiring, we don't need to be so worried about earthing and suchlike. We used an Altronics H0364A case, which is just

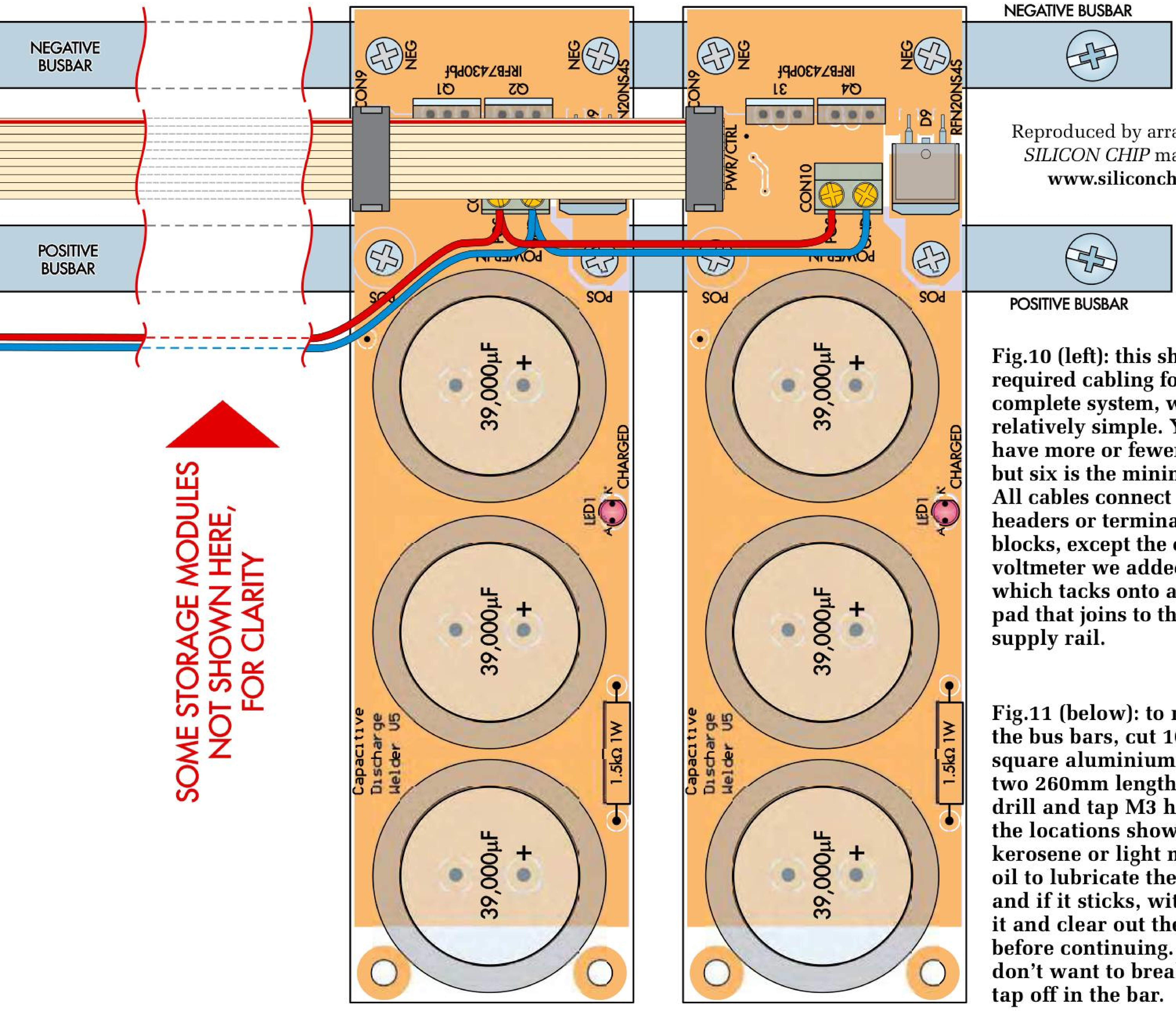

NEGATIVE BUSBAR
POSITIVE BUSBAR
NEGATIVE BUSBAR
POSITIVE BUSBAR
SOME STORAGE MODULES NOT SHOWN HERE, FOR CLARITY
CON9
NEG
IRFB7430PbF
Q1
Q2
Q3
Q4
PWR/CTRL
CON10
D9
RFN20NS4S
POWER IN
POS
39,000µF
+
LED1
A
K
CHARGED
1.5kΩ 1W
Capacitive Discharge Welder V5

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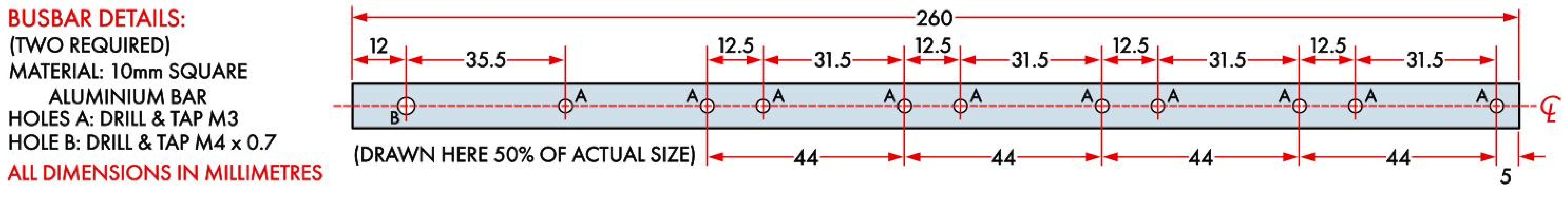
Fig.10 (left): this shows the required cabling for the complete system, which is relatively simple. You can have more or fewer ESMs, but six is the minimum. All cables connect to headers or terminal blocks, except the optional voltmeter we added, which tacks onto a solder pad that joins to the +15V supply rail.

Fig.11 (below): to make the bus bars, cut 10mm square aluminium bar to two 260mm lengths and drill and tap M3 holes in the locations shown. Use kerosene or light machine oil to lubricate the tap and if it sticks, withdraw it and clear out the swarf before continuing. You don't want to break the tap off in the bar.


BUSBAR DETAILS:
(TWO REQUIRED)
MATERIAL: 10mm SQUARE ALUMINIUM BAR
HOLES A: DRILL & TAP M3
HOLE B: DRILL & TAP M4 x 0.7
ALL DIMENSIONS IN MILLIMETRES
(DRAWN HERE 50% OF ACTUAL SIZE)
260
12
35.5
12.5
31.5
12.5
31.5
12.5
31.5
12.5
31.5
44
44
44
44
5
A
B
℄

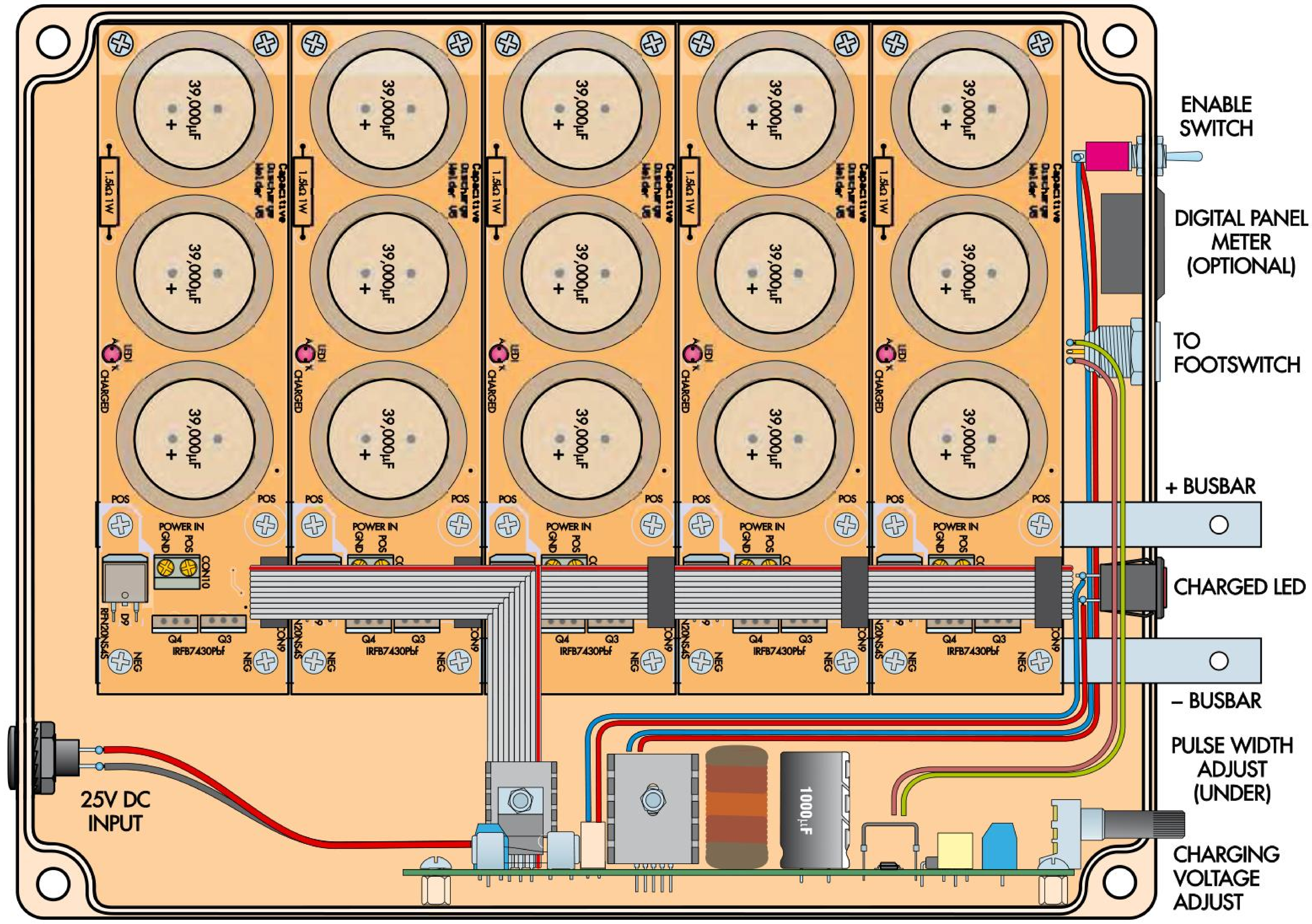

39,000µF
+
1.8kΩ 1W
Capacitive Discharge Welder US
LED1
K
A
CHARGED
POS
POWER IN
GND
POS
CON10
D9
RFN20NS4S
Q4
Q3
IRFB7430Pbf
NEG
CON9
ENABLE SWITCH
DIGITAL PANEL METER (OPTIONAL)
TO FOOTSWITCH
+ BUSBAR
CHARGED LED
– BUSBAR
PULSE WIDTH ADJUST (UNDER)
CHARGING VOLTAGE ADJUST
25V DC INPUT
1000µF

Fig.12: this diagram shows how we mounted the modules in the recommended case and wired them up (62.5% scale).

large enough to fit all the modules. This allows us to mount the ESM 'bundle' on its bus bars in the base with the Power Supply and Controller modules just behind the front panel, secured to the side of the case.

The photograph of the case with the lid off shows this arrangement pretty clearly.

We found that the potentiometer shafts were only just long enough – you might find a better way of mounting these. As our application is stationary in the lab, we used long tie wraps (thick cable ties) to secure the energy store to the case and put firm foam under the lid to hold it all together when the lid is attached.

We folded and mounted a sheet of Presspahn between the output bus bars (visible in the lead photo) to ensure that accidental shorts cannot easily occur. Note that there is no danger here unless the 'trigger' footswitch is pressed, but we do not want any chance of accidentally firing into a dead short. The cutting and folding details for this are shown in Fig.15.

We cut two square holes in the front of the case to allow the bus bars to poke through, shown in Fig.16, along with the other front-panel cutouts. All controls were placed in locations that felt convenient, and we used four holes to fix the Presspahn sheet to the front panel.

We found a cheap voltmeter on eBay and decided to add this – these are available on your favourite auction site for a few dollars if you go looking. We will leave the selection and integration of this to you, as there are many choices out there, and the wiring is pretty straightforward.

Welding!

You will need to experiment to find the settings that work best for you. We used flat AA and D cells to test the system out, and found that with 0.12mm nickel strip, setting the pulse width to maximum and voltage to about 12-14V gave extremely solid welds.

We started with a low voltage and increased the voltage until the welds just stuck, which was about 8V. From that point, we increased the voltage to get a solid weld (in our case, at around 12V), then added a bit.

To test your welds, take pliers and try to pull the tab off. It should be exceptionally well attached and require you to tear the weld 'beads' off.

You will find the copper weld tips wear and get dirty if you experience arcing. Clean them up with sandpaper or a sharp knife for consistent

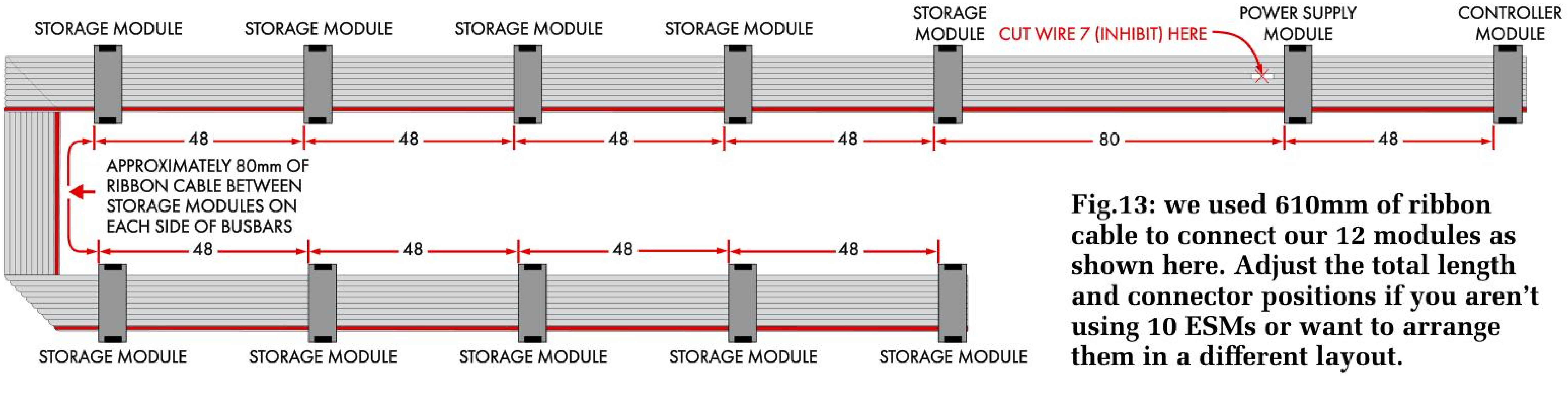
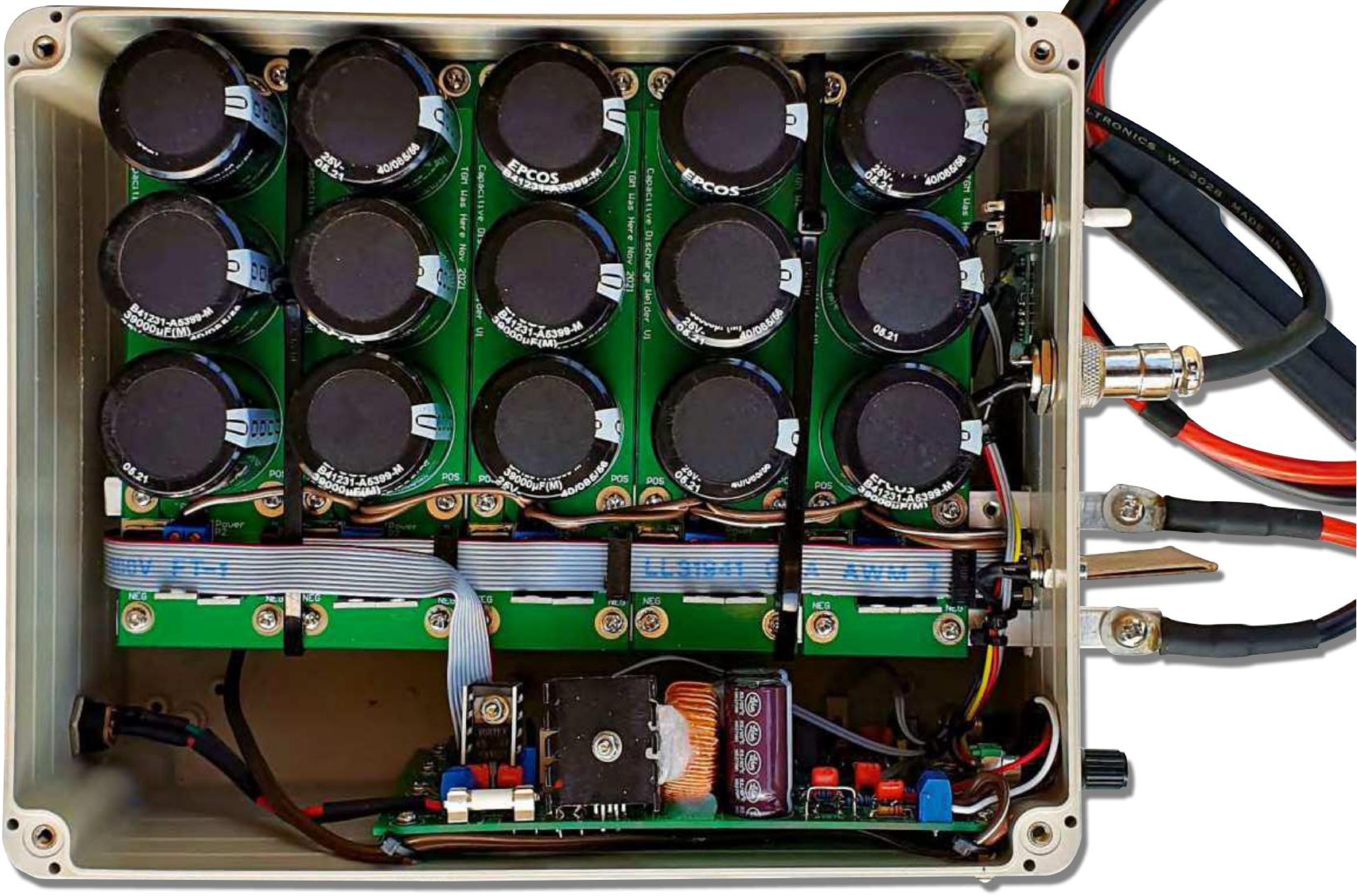

STORAGE MODULE
STORAGE MODULE
STORAGE MODULE
STORAGE MODULE
STORAGE MODULE
CUT WIRE 7 (INHIBIT) HERE
POWER SUPPLY MODULE
CONTROLLER MODULE
48
48
48
48
80
48
APPROXIMATELY 80mm OF RIBBON CABLE BETWEEN STORAGE MODULES ON EACH SIDE OF BUSBARS
48
48
48
48
STORAGE MODULE
STORAGE MODULE
STORAGE MODULE
STORAGE MODULE
STORAGE MODULE

Fig.13: we used 610mm of ribbon cable to connect our 12 modules as shown here. Adjust the total length and connector positions if you aren't using 10 ESMs or want to arrange them in a different layout.



The finished Capacitor Discharge Welder, with the welding cables attached.

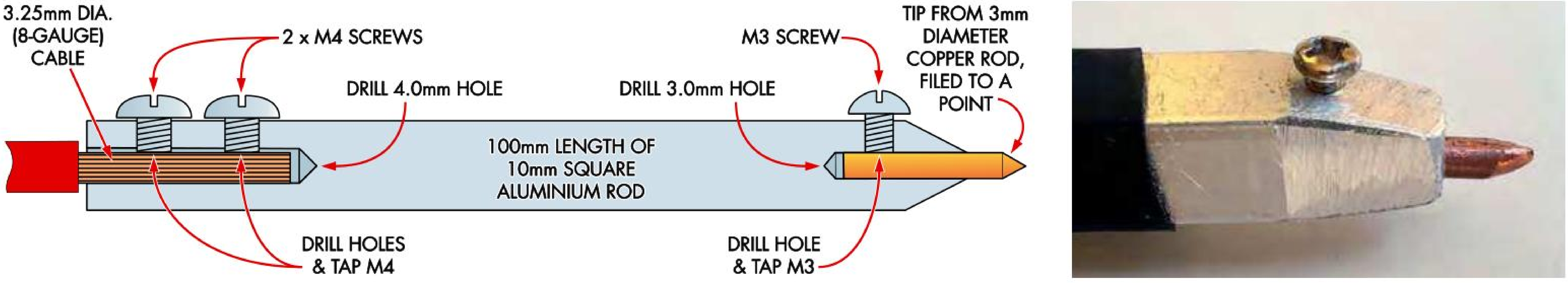

3.25mm DIA. (8-GAUGE) CABLE
2 x M4 SCREWS
DRILL 4.0mm HOLE
DRILL 3.0mm HOLE
M3 SCREW
TIP FROM 3mm DIAMETER COPPER ROD, FILED TO A POINT
100mm LENGTH OF 10mm SQUARE ALUMINIUM ROD
DRILL HOLES & TAP M4
DRILL HOLE & TAP M3

Fig.14: a cross-section of the welding probes we made from 10mm square aluminium bar. The welding tips are 3mm copper rods ground to a sharp point. A close-up of one of the tips is shown adjacent to this diagram.

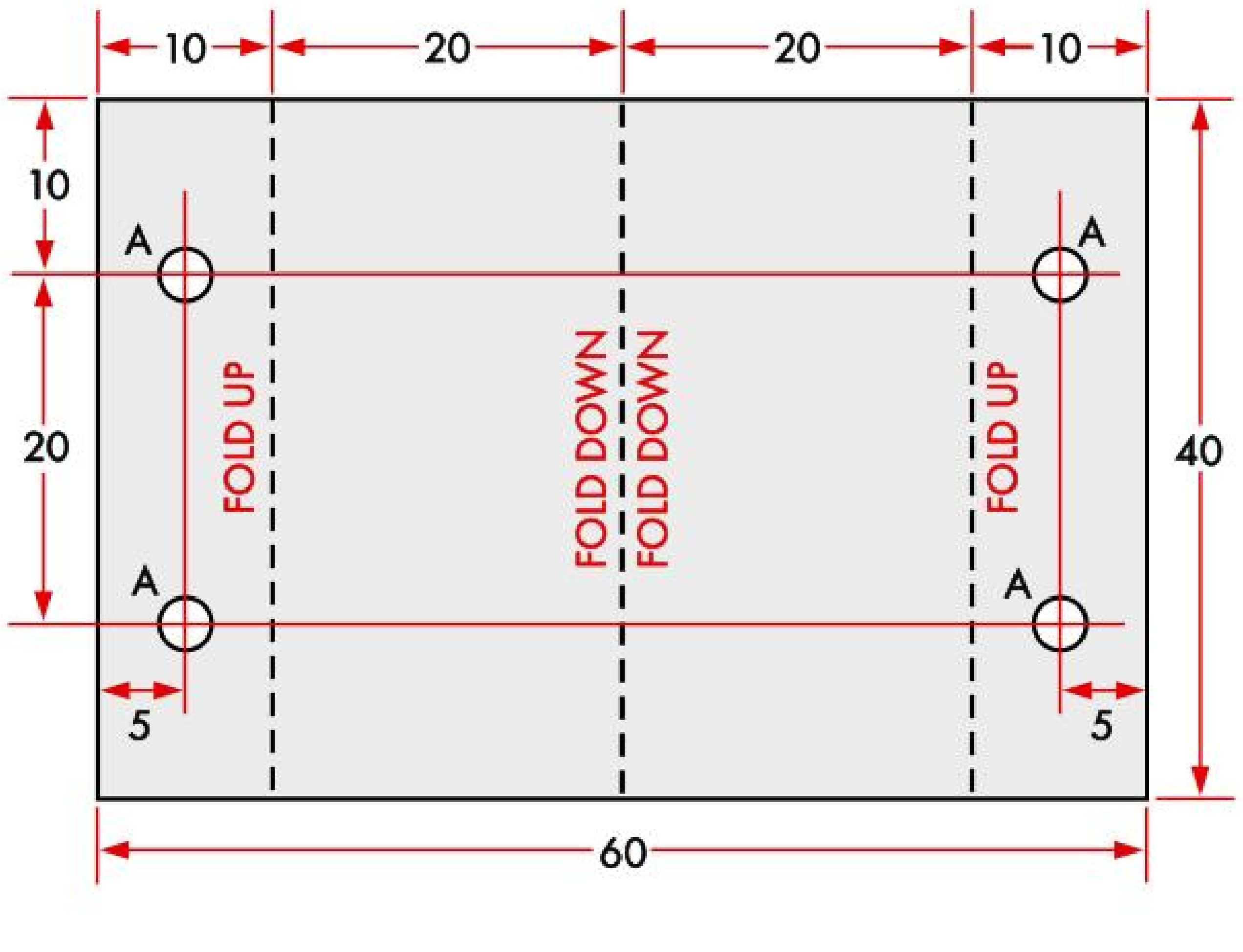
results. Once you have worked your settings out, this *CD Welder* should provide solid service and consistent weld energy.

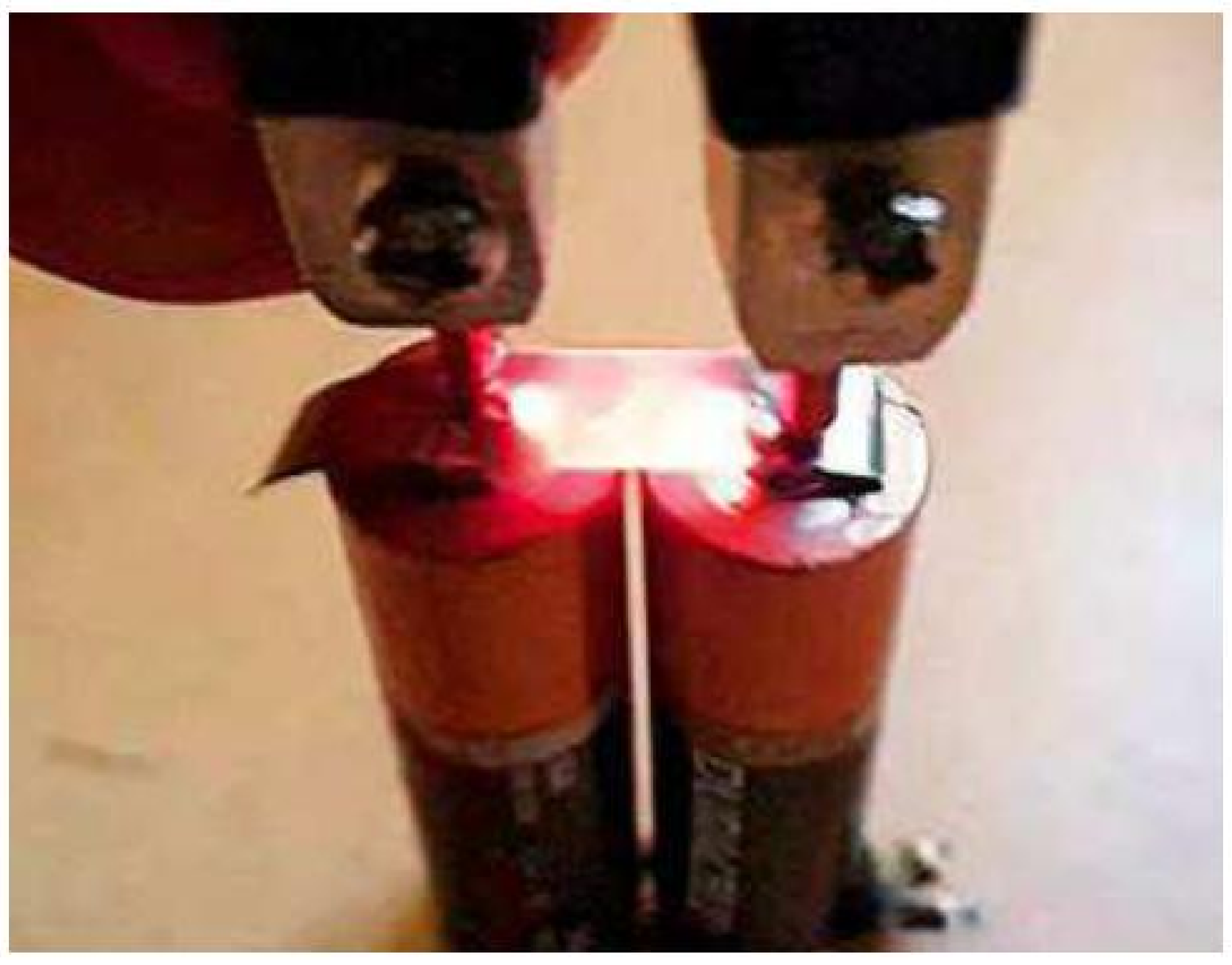
Some tips

- We found 12-15V to be the sweet spot for welding. While we did install 25V capacitors, if you are welding only light gauge battery tabs, you will probably find that you need to charge them no higher than 16V. Then again, you gain a lot of headroom for the slight cost increase of using 25V capacitors.
- To check the effect of weld energy, we welded tabs to the top of a soup can, using this as a battery surrogate. From the outside, the 15V welds are reasonably light 'dimples', while with the 25V welds, some of the tab material has clearly been blown away. This was accompanied by sparks and a flash. The photo of the inside of the can shows that all the welds are visible, but with significantly more damage on the 25V welds.
- Never short the output bus bars directly (with a screwdriver, for example); this will lead to dangerous arcing and quite possibly break something expensive.
- Always wear safety glasses.
- Do not use welding leads with copper wider than 3.3mm in diameter (8 Gauge) or shorter than 1m, as this forms part of the design.

Fig.15: cut, drill and fold the Presspahn as shown here to make the bus bar insulator. This ensures that the Welder cannot be accidentally fired with a short circuit across the bus bars.

Holes A are 3mm in diameter. All dimensions are in millimetres.


10
20
20
10
10
20
40
A
A
A
A
FOLD UP
FOLD DOWN
FOLD DOWN
FOLD UP
5
5
60

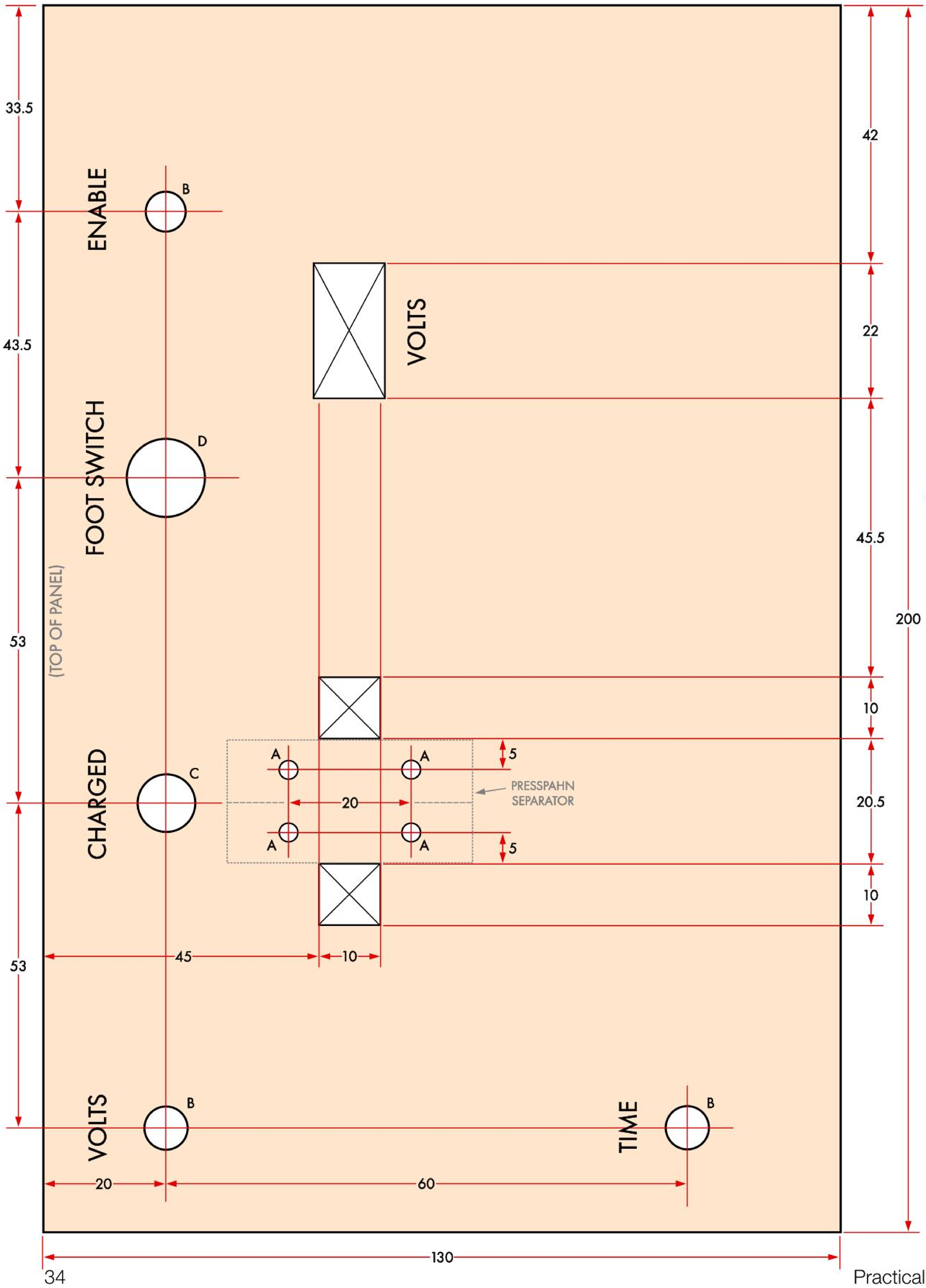


To illustrate the energy involved, and potential danger, this shows the result of placing the probes across the tab between two AA cells. The capacitors were charged to 15V, about 127J of energy.

A look inside a can used for testing. This image shows the damage caused by excessive voltage. The higher energy welds have made holes right through the metal.

- Always keep the leads parallel and never curl them into a coil. Coiling leads will increase inductance in the system and give the flyback diodes a hard time.
- Note that some plug packs have their negative output connected to mains earth. Be careful of these packs as the output leads are at your weld voltage.

Finally, we have a couple of spreadsheets available for download from the April 2023 page of the *PE* website. These include many of the calculations used to verify this design – see: **https://bit.ly/pe-downloads**


33.5
43.5
53
53
ENABLE
B
FOOT SWITCH
D
(TOP OF PANEL)
CHARGED
C
VOLTS
A
A
A
A
20
5
5
PRESSPAHN SEPARATOR
VOLTS
B
TIME
B
45
10
20
60
130
42
22
45.5
10
20.5
10
200

HOLES A: 3.0mm DIAMETER
HOLES B: 6.5mm DIAMETER
HOLE C: 9.5mm DIAMETER
HOLE D: 12.5mm DIAMETER

ALL DIMENSIONS IN MILLIMETRES

Fig.16: the front panel cutting diagram for the layout used in our prototype. This box suits our application in the lab, but you might be able to come up with a better arrangement.

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

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Small-signal PNP transistors	
AC125, NKT214F, OC57 OC59	**£1.00**
Low-noise PNP transistors	
GET106	**£2.50**
Small power PNP transistors	
AC153, AC153K, AC188	**£1.50**
High-voltage PNP transistors	
OC77, CV7001, ACY20	**£1.50**
TO3 PNP power transistors	
OC22, CV7054 (OC23), OC25, OC35, OC36, AD143, AD149, AD161, AD162	**£2.00**
AD140	**£3.50**
AD149 matched pair	**£5.00**
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OC41, OC42, 2SA12, 2SA53,AF124, AF128, GET872A	**£1.50**
NPN transistors	
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Diodes	
ZC5800 RF Schottky	**£0.20**
Low-noise silicon transistors	
BFW16A, 2SC3071	**£1.50**
2SC2204, 2SD655	**£0.50**
ZTX651	**£0.30**
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BF245	**£0.60**
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Exicon 10N20, 10P20	**£6.50**
Hitachi 2SJ99, 2SK343	**£3.50**
Hitachi 2SJ 50, 2SK135	**£7.00**
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BFW11, BFW10, TIS73L, J177, J113, U1994, U1898, 2SJ176	**£1.00**
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5534H metal-cased op amp	**£3.00**
LM384, TDA2030A	**£1.50**
TAA435 (power amp driver)	**£1.20**

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That/dbx 2180 VCA/VCF	**£6.00**
CA3080 VCA/VCF (vocoder)	**£2.80**
CA3082 VCA/VCF	**£4.00**
LM13600/ LM13700 VCA/VCF	**£2.00**
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Dual transistors	
2N2639, 2N2223, 2N2910 (NPN)	**£4.00**
E401 (JFET)	**£4.00**
DMMT3904/6	**£0.50**

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Volt PE165 6.5-inch woofer (each)	**£85**
Morel MDT29 tweeter (each)	**£25**
Kit *pair* of PE165/MDT29 plus Volt crossover parts and PCBs	**£299**
Monacor DT-28N tweeter (each)	**£45**
Vifa 19mm BC20SC15-04 tweeter (each)	**£15**
Volt PE110 5-inch woofer (each)	**£75**
Volt crossover inductors	
1.2mH, 1.5mH, 2mH, 2.7mH, 0.5mH (tapped at 0.3mH) (each)	**£5.85**
LS3/5A transformer-core 15Ω assembled crossover board (each)	**£60**
Fully assembled and tested high-quality speaker prototypes – ask for details	
LS3/5As and other similar speaker systems (pair)	**£200-£350**
Fully tested reclaimed speakers	
Vifa BC14 5-inch woofer (each)	**£15**
Vifa TC26 1-inch tweeter (each)	**£15**
Low-price speakers	
Celestion elliptical 6x4-inch 5Ω (Robert's Radio)	**£3.50**
Philips 4-inch 4070	**£2.00**
EMI 10x6-inch, 30Ω Alnico	**£10**
64mm 64Ω neodymium	**£1.20**
3.5-inch 25Ω	**£3.50**
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CH1
80V
CH2
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- 1 ppm time base accuracy

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CH2
CH3
CH4
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Handyscope HS5-055XMS	*eXtended Memory*	*SureConnect*			HS5-055XMS	£ 993.00
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WiFiScope WS6 DIFF-200S		*SureConnect*			WS6-DIFF-200S	£1,672.00
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Automotive Diagnostic Kit ADK610004DW Pro	*With ATS610004DW-XMSG + ATIS Pro*	TP-ADK610004DW-Pro	£2,928.00
Automotive Diagnostic Kit ADK605004DW	*With ATS605004DW-XMS*	TP- ADK605004DW	£2,195.00
Automotive Diagnostic Kit ADK605004DW Lite	*With ATS605004DW-XMS + ATIS Lite*	TP-ADK605004DW-Lite	£2,352.00
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Automotive Diagnostic Kit ADK5004DW	*With ATS5004DW*	TP- ADK5004DW	£1,957.00
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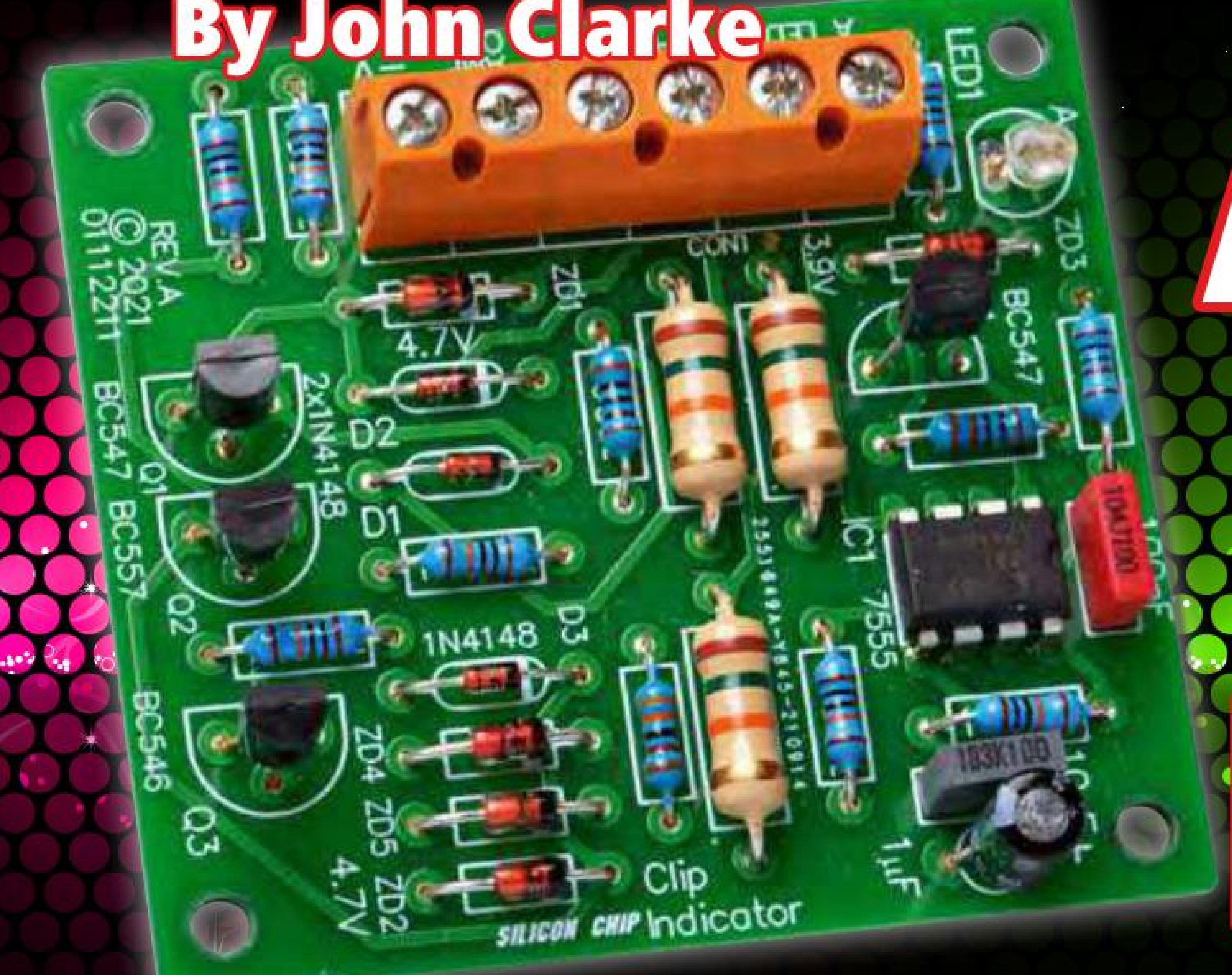


Amplifier Clipping Indicator

Driving an amplifier into clipping can cause unpleasant sounds and even damage expensive speakers. So it is best to find out right away if you're about to run into clipping. This easy-to-build *Amplifier Clipping Indicator* is ideal for that; its LED shows even the briefest of clipping events.

A clipping indicator is a valuable accessory for any audio amplifier. It indicates when the amplifier has reached its limit and is clipping the peaks of the audio signal. In practice, quite a lot of clipping can occur before you notice it and even brief clipping events can cause tweeter damage.

That's because when an amplifier clips, it 'squares up' the waveform; the result contains lots of higher-frequency harmonics, which can easily damage the tweeters in loudspeaker systems.

Our *Amplifier Clipping Indicator* flashes its LED whenever clipping is detected. That's considered to be any time the amplifier output is within about 4V of the positive or negative supply rails. Most amplifiers will clip within about 3V of the supply rail, although some can require slightly more headroom; choosing 4V gives a small safety margin.

There can be a significant ripple on the amplifier supply rails when it's delivering a lot of power (when clipping is most likely to happen). So a proper *Amplifier Clipping Indicator* like this one will compare the output waveform to the instantaneous supply voltages to compensate for that. Its thresholds adapt as power supply voltages fluctuate.

A timer is included to extend the duration of the LED lighting up, to ensure even momentary clipping is visible. The indicator LED is mounted on the *Amplifier Clipping Indicator* PCB, but it also provides a connection for an external LED mounted on the amplifier's front panel.

This *Amplifier Clipping Indicator* is presented as a bare PCB designed to be housed within an existing amplifier. You can build a single unit for a mono amplifier or two for monitoring two channels in a stereo amplifier.

Power for the circuit is derived from the amplifier's supply; it only draws a few tens of milliamps, so it won't affect the amplifier's maximum output power to any significant degree.

When building a stereo version, you could use a single, common LED to indicate clipping from either channel or a separate LED indicator for each channel. The second PCB does not require the full complement of components for the common LED version.

Circuit

The clipping detector circuit is shown in Fig.1. A few components don't have values: resistors R1a, R1b, R2 and R3 and zener diodes ZD4 and ZD5. Their values depend on your amplifier's power supply voltage. Table 1 shows the component values required to suit amplifiers with supplies ranging from ±10V to ±80V.

The clipping detector generates positive and negative reference voltages. For the positive reference, zener diode ZD1 generates a voltage about 4.7V below the V+ positive rail. Resistors R1a and R1b limit the current through ZD1 to approximately 10mA; together, they connect across the V+ and 0V amplifier supply rails. The generated voltage is shown on the circuit as V+ – 4.7V at Q1's emitter.

The 4.7V between this rail and V+ is also used to power timer IC1. We allow 5mA for IC1's supply and 5mA to bias ZD1. More on IC1's operation later.

Zener diode ZD2 and resistor R2 between the V– supply and 0V generate the negative reference; R2 limits the current through ZD2 to about 5mA.

Detecting positive clipping

The positive reference voltage (V+ – 4.7V) is connected to the emitter of NPN transistor Q1. Its base goes to the amplifier's output via a 100kΩ current-limiting resistor, while diode D2 stops Q1's base-emitter junction from being reverse-biased.

Just before clipping, the amplifier output voltage will rise above the V+ – 4.7V reference plus Q1's base-emitter on-voltage of about 0.7V. Q1 switches on when the amplifier output voltage is within 4V of the positive supply. It then sinks current via diode D1, the 100Ω resistor and zener diode ZD3.

The anode of ZD3 connects to the pin 2 trigger input of IC1, and as this voltage drops, timer IC1 starts running. This means that IC1's pin 3 output goes high, switching on Q4 and the indicator LED (LED1) via a 1kΩ current-limiting resistor. A second external LED will also be lit if connected to the external LED connections.

IC1 is a CMOS version of the 555 timer and is set up to operate as a monostable timer. Timing is initiated when the pin 2 trigger input goes below a third of its supply voltage. With a 4.7V supply, the trigger point is 1.56V above the V+ – 4.7V rail or 3.13V below the V+ supply rail.

Pin 2 is usually held at V+ by a 100kΩ pull-up resistor. However, when current flows through ZD3, D1 and Q1, the voltage at pin 2 goes low enough to trigger the timer.

Once the pin 3 output goes high, the 1µF capacitor at pins 6 and 7 of IC1 begins to charge from the V+ supply through a 100kΩ resistor. When the capacitor reaches two thirds of the supply (3.13V above the V+ – 4.7V reference), the pin 3 output goes

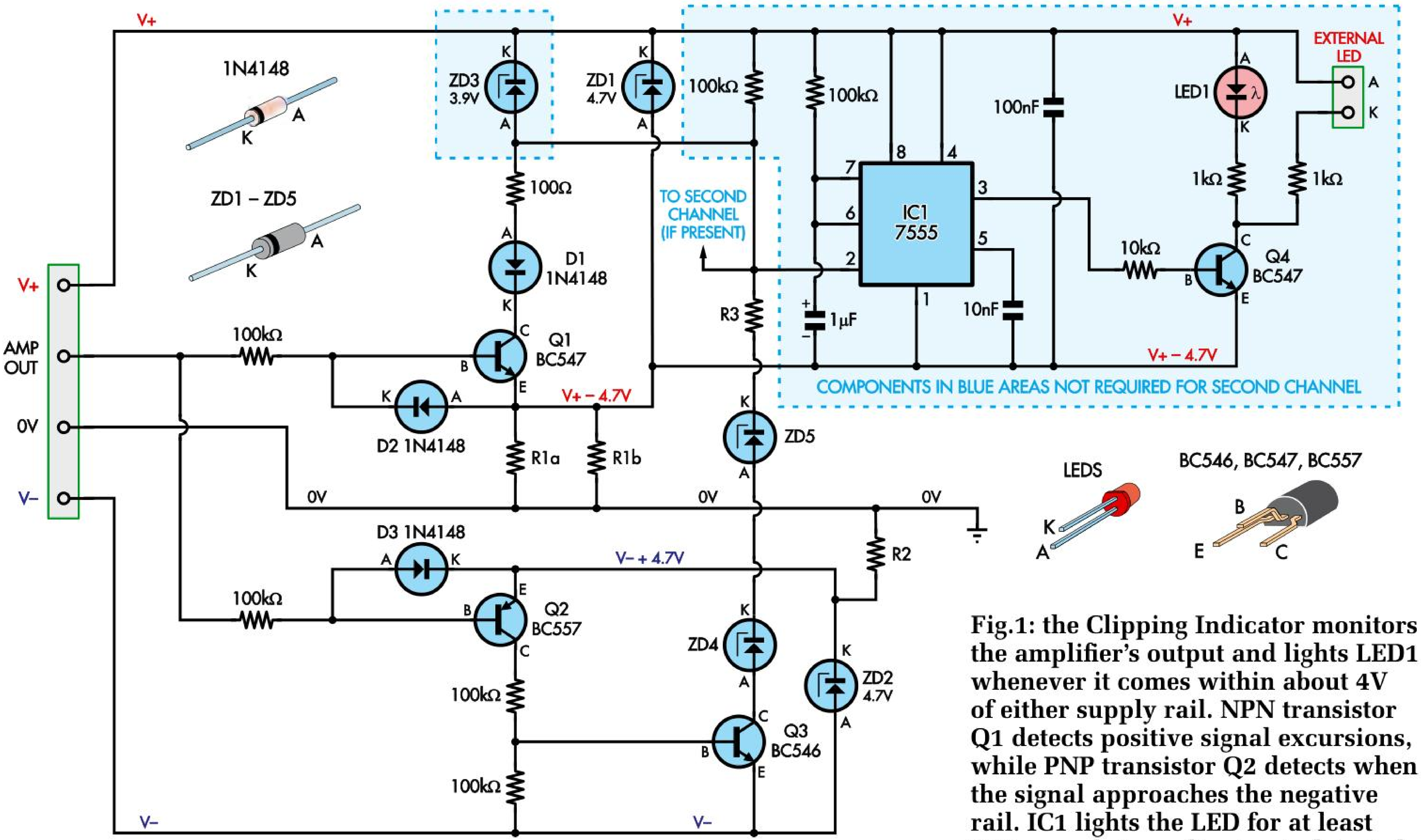


Fig.1: the Clipping Indicator monitors the amplifier's output and lights LED1 whenever it comes within about 4V of either supply rail. NPN transistor Q1 detects positive signal excursions, while PNP transistor Q2 detects when the signal approaches the negative rail. IC1 lights the LED for at least 110ms each time clipping is detected.

Amplifier Clipping Indicator

low, and this capacitor discharges into pin 7.

This sequence of events occurs when the trigger voltage at pin 2 is only low for a very short period. If the trigger voltage is low for longer than the timing period, the pin 3 output will stay high until pin 2 goes high again.

The timing period is about 110ms, as set by the 100kΩ resistor and 1µF capacitor values. IC1 acts as a pulse extender for brief detection of amplifier clipping. It ensures that clipping is shown on the LED for at least 110ms (ie, a bit more than 1/10th of a second).

Detecting negative excursions

ZD2, PNP transistor Q2 and diode D3 work to detect negative excursions from the amplifier. When the amplifier output swings low, within 4V of the negative supply, transistor Q2 switches on and, in turn, switches on transistor Q3. This then pulls the pin 2 trigger input of IC1 low via two series zener diodes (ZD4 and ZD5) and resistor R3.

Transistor Q3 is rated for a maximum collector-emitter voltage of 80V. Without the two zener diodes, the transistor could be subject to the total of the V+ and V– supply rails and so would only be suitable for use with a maximum of ±40V supply rails. By including the zener diodes, the voltage at the collector is reduced to a maximum of around 66V.

While we could have used a transistor with a higher voltage rating, they are not as readily available as the BC546. Table 1 shows the required values for resistors R2, R3 and zener diodes ZD4 and ZD5 for various amplifier supply voltages.

Resistor R3 is included to limit current in zener diode ZD3 when transistor Q3 conducts.

While this is not the simplest clipping detector circuit, it has the advantage of presenting an almost entirely linear load to the amplifier output, to minimise the possibility of any distortion due to loading.

Note that if you want to monitor clipping in a stereo amplifier and use a single indicator LED, you can dispense with the components in the blue shaded areas for the second channel. Interconnection is made between the two PCBs at the top end of R3. This way, a clip event at either input will trigger IC1 on the board where it is fitted.

Alternatively, you can build two complete copies of the circuit for independent channel clipping indication. The boards are small and can be stacked to take up relatively little room.

Construction

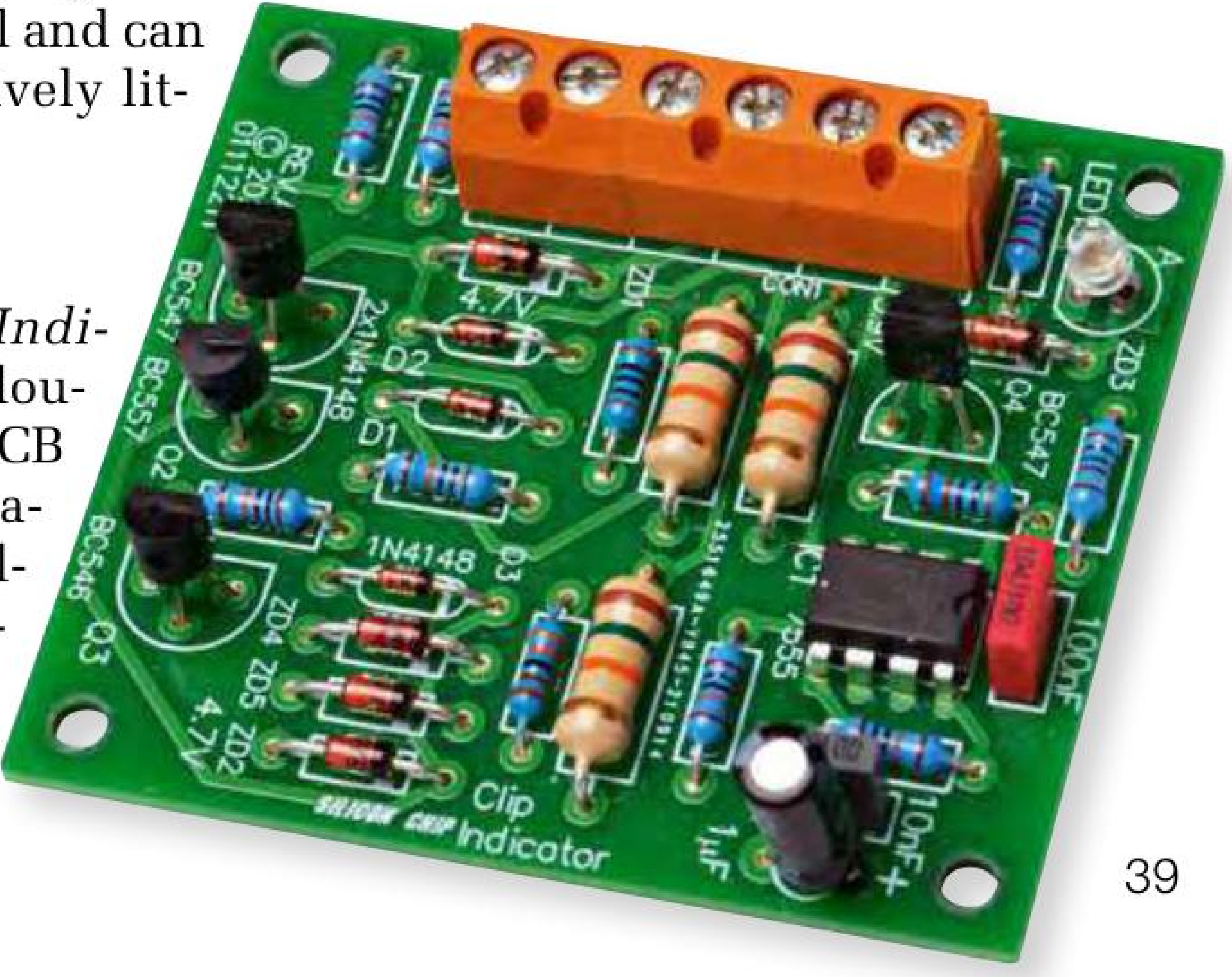
The *Amplifier Clipping Indicator* is constructed on a double-sided, plated-through PCB coded 01112211 that measures 54 x 60mm and is available from the *PE PCB Service*. There are two overlay diagrams shown. Fig.2 is the version used for a mono amplifier, or for the left channel in a stereo amplifier (or both channels if you want independent clip indication).

If the second channel is built as shown in Fig.3, clipping in either channel will be indicated with a single LED.

Begin by fitting the resistors. First, refer to Table 1 to select the resistor value and power ratings for R1a, R1b, R2 and R3. (Ideally, you should check each resistor using a digital multimeter (DMM) before installing it.

Once these parts are in place, follow with diodes D1, D2 and D3, orienting them correctly. The zener diodes can be mounted next. ZD1 and ZD2 are 4.7V types, while ZD3 is rated at 3.9V. The ZD4 and ZD5 voltages are as per Table 1, or replaced with a wire link if indicated.

Transistors Q1, Q2, Q3 and Q4 can be mounted next. There are three different types (although Q1, Q3 and Q4



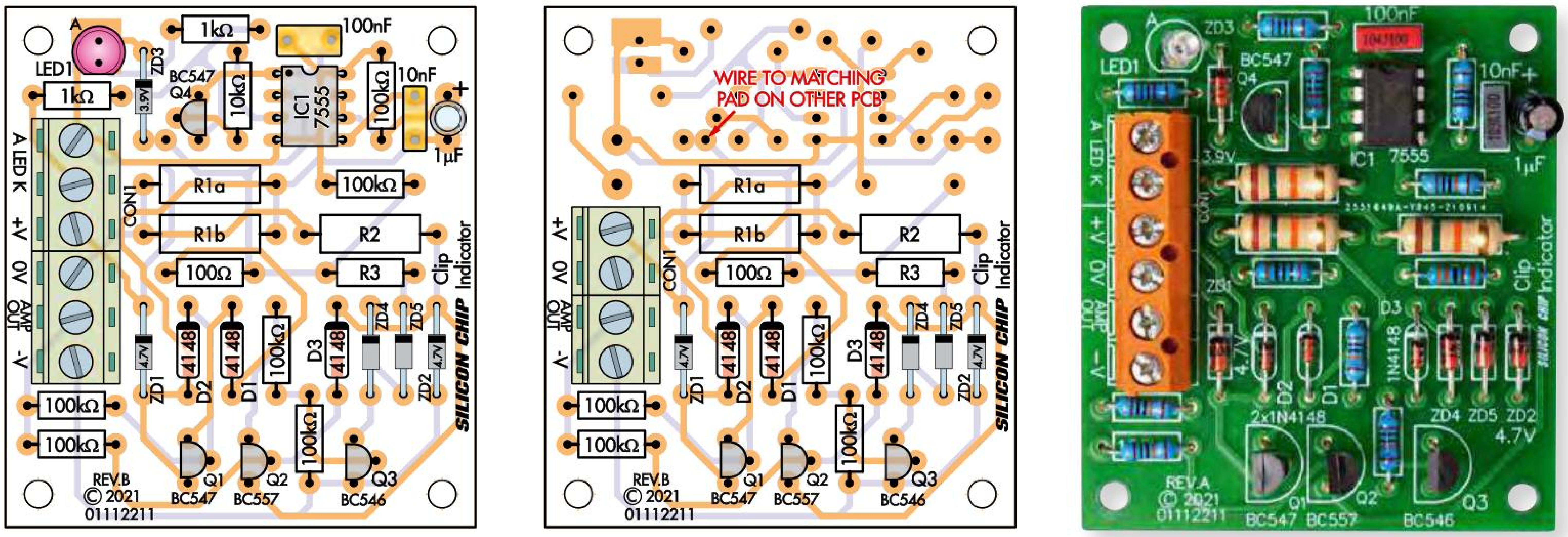


Fig.2 and Fig.3: the board is not difficult to assemble; the components are fitted as shown at left. The diodes, LED, IC and electrolytic capacitors are polarised. If you're building a mono version or a stereo version to drive two independent LEDs, build the fully populated version. For a stereo version with a single clip indicator LED, build one of each version and join the indicated pad between the two boards (not present on the prototype PCB pictured).

can all be BC546s if desired), so take care to install each in its correct place.

The screw terminal blocks making up CON1 need to be joined together first by fitting each side-by-side by sliding the dovetail mouldings together. Solder them in place with the wire entry side of the terminals facing the nearest edge of the PCB.

Now fit LED1 with its longer lead inserted into the anode hole. Mount it so that the top is about the same level as the adjacent screw terminal.

IC1 can be soldered directly onto the PCB, making sure its pin 1 is facing as shown. Finally, install the capacitors. The 1µF capacitor must be oriented correctly, with its longer + lead into the pad shown. You could use a non-polarised 1µF plastic film capacitor, but it will be substantially larger and probably more expensive than the electrolytic.

If you're building the two-channel version to light a single clip indicator LED, build a second board as per Fig.3 and solder a ~20mm length of solid-core 'Bell wire' to the top of that board, into the pad between ZD3 and Q4. It makes sense for the more sparsely populated board to be at the bottom of the stack as it lacks the LED, and you'll want to be able to see the LED on the other board.

Alternatively, if you're building a two-channel version with separate LED indicators, make a second identical board and don't fit the vertical wire.

Mounting it and wiring it up

Use the board to mark out four holes in a convenient location within the amplifier chassis, ideally, between the amplifier modules and speaker terminals, or at least near the terminals.

If it's a stereo amplifier, you can stack the two boards by feeding longer machine screws up through the spacers on which the lower board is mounted, then screwing some ~16mm tapped spacers on top of the threads once the first module is in place. If you have space, you could mount the two modules separately, eg, side-by-side.

Connect the *Amplifier Clipping Indicator(s)* to the amplifier's V+, V– and 0V supply rails and the amplifier speaker + output(s) to AMP OUT input(s) on the *Clipping Indicator* module(s). Make sure the wiring is suitably voltage-rated, especially when the supply rails are at high voltages from earth.

The external LED connects to the A and K terminals on the board. If you are building the minimised stereo version with IC1 and associated components missing, feed the wire you soldered earlier to the bottom board up through the matching pad on the top board. Solder it on top and mount the upper board using longer tapped spacers and short M3 machine screws.

In all cases, when using a second *Amplifier Clipping Indicator* module,

Table 1 – component values that vary with amplifier supply rail voltages

Supply	R1a	R1b	R2	R3 (½W)	ZD4	ZD5
±80V	15kΩ 1W	15kΩ 1W	15kΩ 1W	33kΩ	75V (1N4761)	18V (1N4746)
±75V	15kΩ 1W	15kΩ 1W	15kΩ 1W	33kΩ	75V (1N4761)	9.1V (1N4739)
±70V	12kΩ 1W	12kΩ 1W	12kΩ 1W	33kΩ	75V (1N4761)	wire link
±65V	12kΩ 1W	12kΩ 1W	12kΩ 1W	33kΩ	33V (1N4752)	33V (1N4752)
±60V	12kΩ 1W	12kΩ 1W	12kΩ 1W	33kΩ	27V (1N4750)	27V (1N4750)
±55V	10kΩ ½W	10kΩ ½W	10kΩ ½W	33kΩ	22V (1N4748)	22V (1N4748)
±50V	9.1kΩ ½W	9.1kΩ ½W	9.1kΩ ½W	33kΩ	16V (1N4745)	18V (1N4746)
±45V	8.2kΩ ½W	8.2kΩ ½W	8.2kΩ ½W	33kΩ	12V (1N4742)	12V (1N4742)
±40V	7.5kΩ ½W	7.5kΩ ½W	7.5kΩ ½W	30kΩ	15V (1N4474)	wire link
±35V	6.2kΩ ½W	6.2kΩ ½W	6.2kΩ ½W	30kΩ	3.9V (1N4730)	wire link
±30V	5.1kΩ ½W	5.1kΩ ½W	5.1kΩ ½W	27kΩ	wire link	wire link
±25V	3.9kΩ ½W	3.9kΩ ½W	3.9kΩ ½W	22kΩ	wire link	wire link
±20V	3kΩ ½W	3kΩ ½W	3kΩ ½W	18kΩ	wire link	wire link
±15V	2kΩ ½W	2kΩ ½W	2kΩ ½W	13kΩ	wire link	wire link
±10V	1kΩ ½W	1kΩ ½W	1kΩ ½W	8.2kΩ	wire link	wire link

all three supply connections must be made to both boards, along with the AMP OUT terminal. The only terminals that aren't needed on the board with components missing are the LED A and K.

The external LED or LEDs can be attached to the amplifier chassis using suitable LED bezels, or (less ideally) glued into tight-fitting holes using neutral-cure silicone sealant.

Parts List – Clipping Indicator (per channel)

1 double-sided, plated-through PCB coded 01112211, 54 x 60mm available from the *PE PCB Service*
2 3-way screw terminals with 5.08mm spacing (CON1) ***OR***
2 2-way screw terminals with 5.08mm spacing (CON1; for minimised second channel)

Semiconductors
1 7555 CMOS timer, DIP-8 (IC1•)
2 BC547 or BC546 NPN transistors (Q1, Q4•)
1 BC557 PNP transistor (Q2)
1 BC546 NPN transistor (Q3)
1 yellow, amber or red 3mm or 5mm LED (LED1•)
1 yellow, amber or red LED (**optional**; external LED•)
2 4.7V 1W (1N4732) zener diodes (ZD1, ZD2)
1 3.9V 1W (1N4730) zener diode (ZD3•)
3 1N4148 small-signal diodes (D1-D3)
2 zener diodes or wire link (ZD4▲, ZD5▲)
1 LED bezels (**optional**; for chassis-mounting external LED)
4 M3 x 6mm tapped nylon spacers (or 15mm spacers for the upper board in the stack)
8 M3 x 6mm machine screws (or 4 M3 x 15mm machine screws for the upper board in the stack)
1 20mm+ length of solid-core hookup wire (**optional**; to join stacked stereo version)
Various differently coloured hookup wires, rated for amplifier supply voltage

Capacitors
1 1µF 16V PC electrolytic•
1 100nF 63V or 100V MKT polyester•
1 10nF 63V or 100V MKT polyester•

Resistors *(¼W, 1% axial metal film)*
6 100kΩ (• 4 required for minimised version)
1 10kΩ•
2 1kΩ•
1 100Ω
4 other resistors, values as per Table 1▲
• not required for the minimised second channel
▲ see Table 1 for values and power ratings

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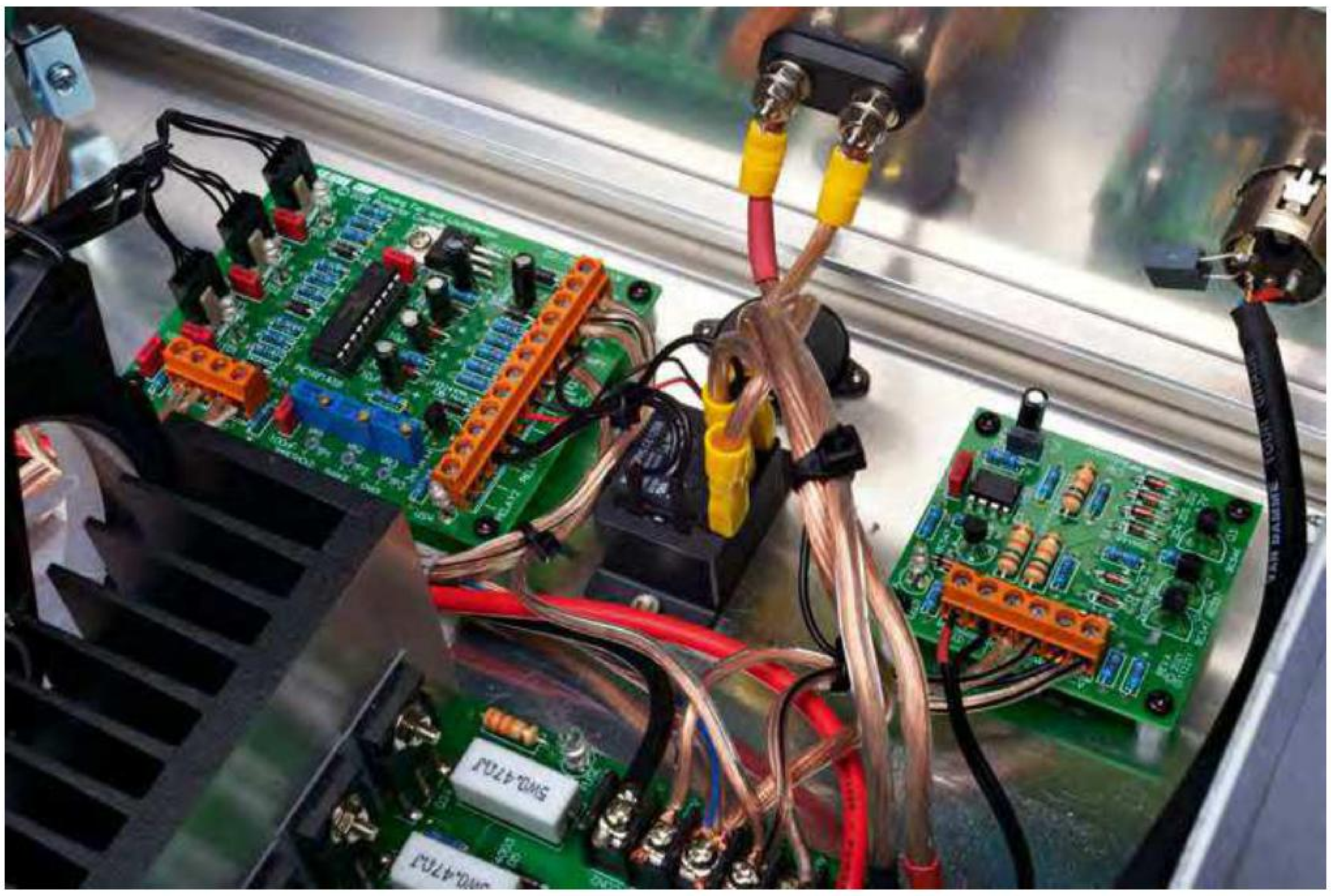

This shows the Clipping Indicator installed inside our 500W Amplifier chassis (see p.17 for more details).

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By Jim Rowe

Three low-noise HF-UHF Amplifiers

输入
RFin
20dB
1=75mA
输出
RFout
单级宽带射频放大器LNA-V1.0
GND
VCC
RFin
RFout
+5V@90mA
Freq:50M-4G
→IN OUT→
NF:0.6dB

Left-to-right: module one (1MHz-3GHz), module two (5MHz-6GHz), module three (50MHz-4GHz)

All three of these low-cost wideband HF-UHF amplifier modules claim to provide 20dB of gain, over frequency ranges of 1MHz to 3GHz, 5MHz to 6GHz and 50MHz to 4GHz. They vary mainly in terms of size, shielding, supply voltage and price.

The 1MHz to 3GHz module is the largest, with a PCB measuring 50 x 50mm. It has SMA input and output connectors at each end and a mini 2-way terminal block for the power connections at the rear. The amplifier circuitry is inside a 32 x 30 x 6.5mm shielding box in the centre of the PCB, visible in the photo below. There's also a small power indicator LED at upper right (D2).

This module is currently available online from Amazon UK (and others) for around £9 and up, including delivery – search for '1-3000MHz 2.4GHz 20dB RF Broadband Low Noise Amplifier Module UHF HF VHF'. It's the cheapest of the three amplifier modules we're describing.

It has been designed to run from a 12V DC supply, with a stated current drain of 75mA. It has a maximum input level of 0dBm, and the maximum output power is said to be +19.5dBm (approximately 100mW). While it's described on the PCB as a low-noise amplifier (LNA), no noise figure (NF) is given.

I could find no information regarding its internal circuit, or the active devices inside. But when I powered it up and checked its gain with my Signal Hound SA44B spectrum analyser and TG44A tracking generator (controlled using their Spike software), the results were quite impressive, as you can see from the red trace in Fig.1.

The gain measured about 21dB at the low end, drooping fairly smoothly to 13.5dB at 3GHz, and then wobbling up and down a bit before falling to 3dB at about 4GHz. That's not bad for a low-cost module with a rated frequency range of 1MHz to 3GHz.

I don't have the equipment to measure the NF, but I was able to use the SA44B with Spike to measure the module's DANL (distortion and noise level) at 1GHz and 3GHz with a 50Ω input termination. I then compared these measurements with the DANL of the SA44B alone (50Ω input termination) at the same frequencies.

The results showed a rise in the DANL from –153dBm to –138dBm at 1GHz (+15dB), and a rise in DANL from –149dBm to –139dBm at 3GHz (+10dB). This is perhaps not good enough to qualify the module as an LNA, but quite acceptable for many possible applications.

I also checked the module's current drain from the 12V supply, and it measured precisely 75mA.

So overall, this module is a good choice if you only need to amplify signals at frequencies up to about 3GHz, and would be happy with the gain curve shown in red in Fig.1, the maximum output of 100mW and the modest noise performance. It would likely provide a good way to boost the output from a drone control transmitter, for example.

The second module

The next amplifier module is physically smaller, with a PCB measuring 33 x 24.5mm and again with SMA input and output connectors at each end. This module doesn't come with a mini two-way terminal block fitted to the PCB for power, but there are two pads at top centre ready to mount such a block (on either side of the PCB).

The amplifier circuitry is again inside a shielding box in the centre of the PCB, measuring 18.5 x 14.5 x 3.5mm. There is no power indicator LED.

This module is available from Banggood (code 1119141) – **https://bit.ly/pe-apr23-amp2** – for around $16, plus shipping from China (free for orders over $50).

It is designed to operate from a 5V DC supply, with a nominal current drain of 85mA, so it can be powered from a standard USB power pack. Again, it is claimed to provide a nominal gain of 20dB, this time from 5MHz to 6GHz, with a maximum input level of 0dBm. The maximum output power is stated to be +21dBm (around 120mW) at the 1dB compression point. This module doesn't claim to be an LNA.

供电
GND
型号：中功率.1
供电电压：+12v
频率：1m-3GHz
增益：20dB
其他：1=75mA
输入
输出
RFin
RFout
单级宽带射频放大器LNA-V1.0
5

Module one is the largest of the three, measuring 50 x 50mm, it uses a two-way screw terminal block for the power connection.

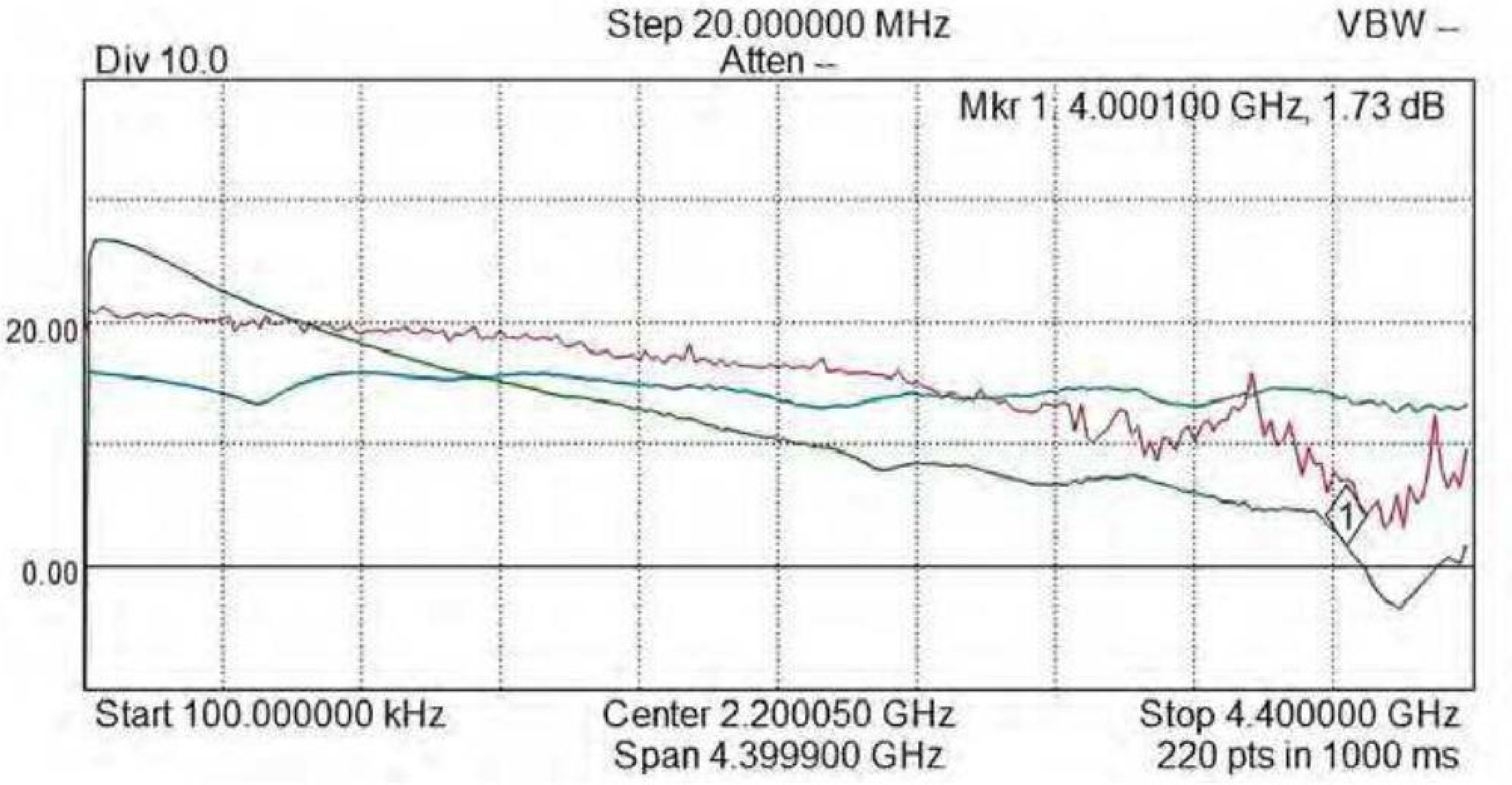


Fig.1: the gain curve for the three modules – red (1MHz-3GHz), blue (5MHz-6GHz), green (50MHz-4GHz).

I could find very little information regarding this module's internal circuitry, apart from the suggestion that it's based on a Qorvo SBB5089Z InGaP MMIC (monolithic microwave integrated circuit) amplifier device. This comes in a 3- or 4-pin SOT-89 package, and in the data sheet, Qorvo gives the circuit for an evaluation board which I have redrawn in Fig.2. That is a pretty standard MMIC circuit, and probably close to what is inside this module.

When I powered it up, the first thing I checked was its current drain from a 5V power pack. This turned out to be 36mA, less than half the claimed nominal value of 85mA. However, the current might increase when the module is delivering its maximum output power of +21dBm.

Next, I checked its gain with my Spike test setup. This combination only goes up to 4.4GHz, but the result is shown in blue in Fig.1. As you can see, it was pretty respectable over this range, varying between about 13.5dB and 16.5dB with an average value of around 15dB.

The Qorvo data sheet for the SBB5089Z suggests that it probably extends to provide at least 14.5dB of gain at 6.0GHz, but I can't confirm that.

After this, I used the SA44B with Spike to measure this module's DANL at 1GHz and 4GHz with a 50Ω input termination, and again compare them with the figures for the SA44B alone, at the same frequencies. The results this time showed a rise in the DANL from –153dBm to –140dBm at 1GHz (+13dB), and a rise from –140dBm to –132dBm at 4.0GHz (+8dB).

This is a little better than the results for the first module, but still perhaps not good enough to be regarded as an LNA, even though it would be quite acceptable for many applications.

So this module would probably be a good choice if you want to amplify signals at frequencies above 3GHz, up to about 6GHz, and would be happy with the gain curve shown in Fig.1 (blue trace) and its ability to deliver up to approximately 120mW. The noise performance is not too bad, either.

On the down side, this module will cost you a little more than the first one, and doesn't come with a terminal block already fitted. But its smaller size might make it easier to fit into equipment like a drone control transmitter.

The third module

The final amplifier module we're looking at differs from the other two as it is completely housed in a cast aluminium case, so it's fully shielded. The case measures 42 x 32 x 12mm, with the SMA input and output connectors at each end and an insulated feed-through pin fitted to the rear of the case for its power input.

A small solder lug held by the feed-through pin's external body allows for the connection of the negative power lead.

GND
VCC
RFin
RFout
Gain: 20dB
Voltage: +5V

The second module is the smallest and most sparse of the three. It only has two unused pads for the power connection.

This module is available from Amazon UK (and others) for around £19 and up, including delivery – search for '50M-4GHz Low Noise Amplifier 0.6dB RF LNA Amplifier'.

Like the second module, this one operates from a 5V DC, with a nominal current drain of 90mA. So again, it can be powered from a standard USB power pack.

The nominal bandwidth is 50MHz to 4.0GHz, with a typical gain of 19dB and a maximum output power of +22dBm (about 150mW) for 1dB compression at 2GHz. The maximum input signal level is stated as less than +10dBm, or 10mW.

The noise figure is quoted as typically 0.6dB, suggesting that this module is intended for use as an LNA to boost the sensitivity of receivers and test equipment like spectrum analysers.

I measured its current draw at 82mA, just a little lower than the claimed value, but as before, this was when the module's input was terminated with 50Ω. It will likely rise when the module is handling an RF signal.

Next, I checked its gain, as before with the SA44B/TG44A/Spike test setup. The result is shown in green in Fig.1. The gain is highest at around 50MHz (27dB), drooping down to around 15dB at 1.32GHz, 10dB at 2.2GHz and 2dB at around 4.0GHz.

This is a little disappointing, considering the amplifier is claimed to have a gain of 18dB and a bandwidth of 50MHz to 4.0GHz, but it would still be quite useful if you are mainly dealing with signals below 1.8GHz.

As noted earlier, I don't have the equipment to measure the NF directly. But when I used the SA44B spectrum analyser with Spike to compare the amplifier's DANL at 1GHz and 4GHz against that of the SA44B alone (in each case with a 50Ω input termination), the results were noticeably better than for the other two modules.

At 1GHz, the DANL rose from –153dBm to –143dBm (+10dB), while at 4GHz the DANL rose from –140dBm to –135dBm; a rise of only 5dB. So it might be a bit lacking in terms of gain and bandwidth, but it probably does qualify as an LNA.

The bottom line

Based on these test results, each module has strengths and weaknesses. The best choice depends on the gain and bandwidth you need, the kind of application you want to use the amplifier for and how much you can pay.

For example, the second module offers the best gain/bandwidth

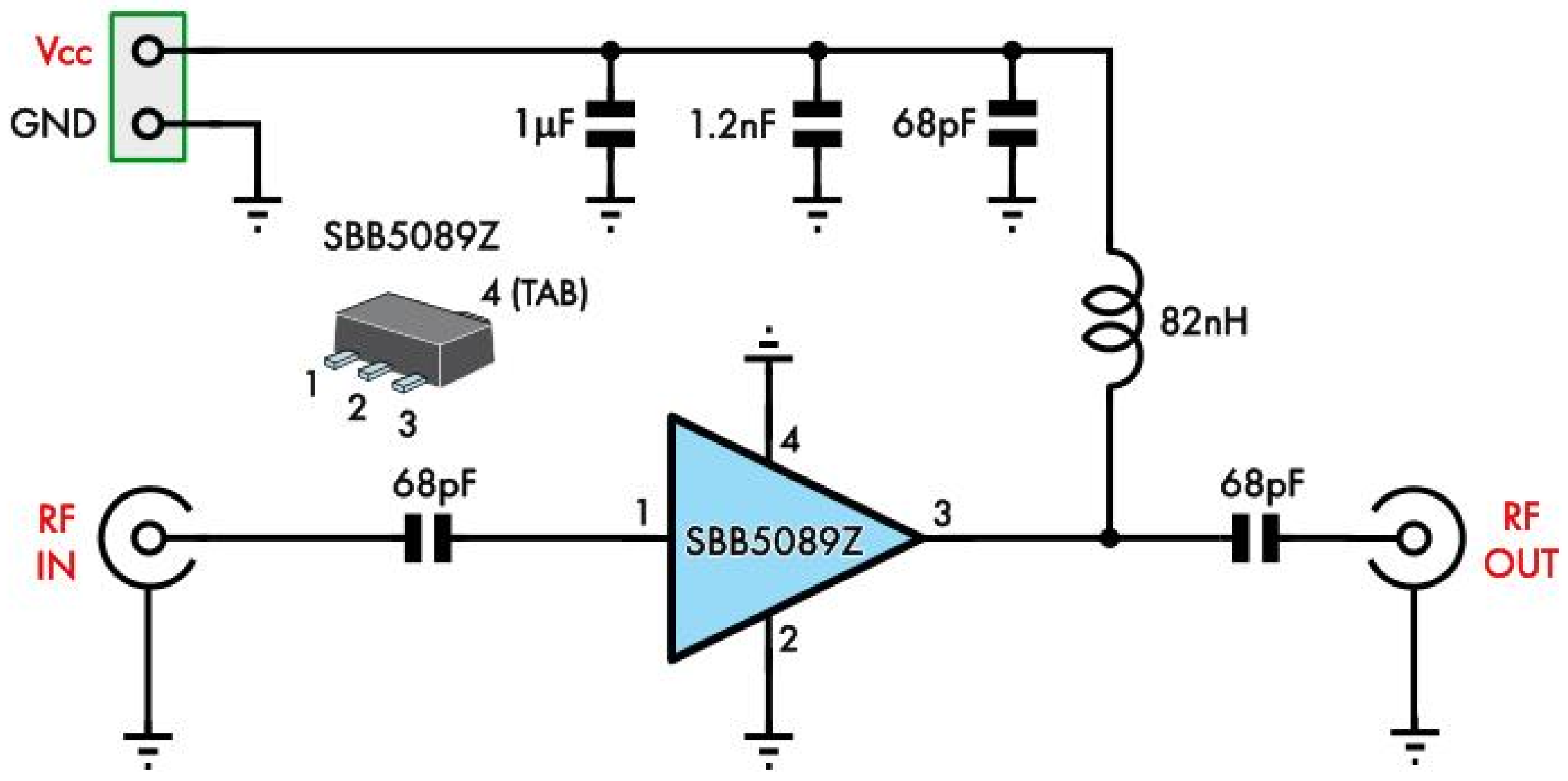


Fig.2: little information is given on the 5MHz-6GHz module, so the circuit shown is based on a Qorvo SBB5089Z-based evaluation board. It should be close to what the module is comprised of.

performance, coupled with a reasonable noise performance and the ability to provide an output of around 100mW. It's also not that much more expensive than the cheapest (first) module, so it is probably the best choice for applications like boosting the output of a drone control transmitter.

But the first module provides much the same performance at frequencies below 3GHz, so with its lower price, it is an attractive choice for the same kind of application.

Suppose you are mainly interested in signals below about 1.8GHz and noise performance is critical, such as boosting the signals going into a receiver or spectrum analyser. In that case, the third module is probably the best choice, despite its significantly higher price.

Using these amps with the LTDZ V5.0 spectrum analyser

You might recall that towards the end of my review of the low-cost LTDZ V5.0 spectrum analyser (*PE*, February 2022), I mentioned that I would be testing this type of amplifier module to see whether they could be used to improve that device's sensitivity.

That's because the LTDZ analyser has a relatively high noise floor of about –77dBm, meaning that any signals lower than this (or possibly even slightly higher) would essentially be 'lost in the noise'. An LNA could be used to boost these signals well above the noise floor, allowing them to be distinguished and measured.

After checking out the three modules reviewed here, I decided that the second and third (LNA) modules would be the best candidates for this job, so I tested both.

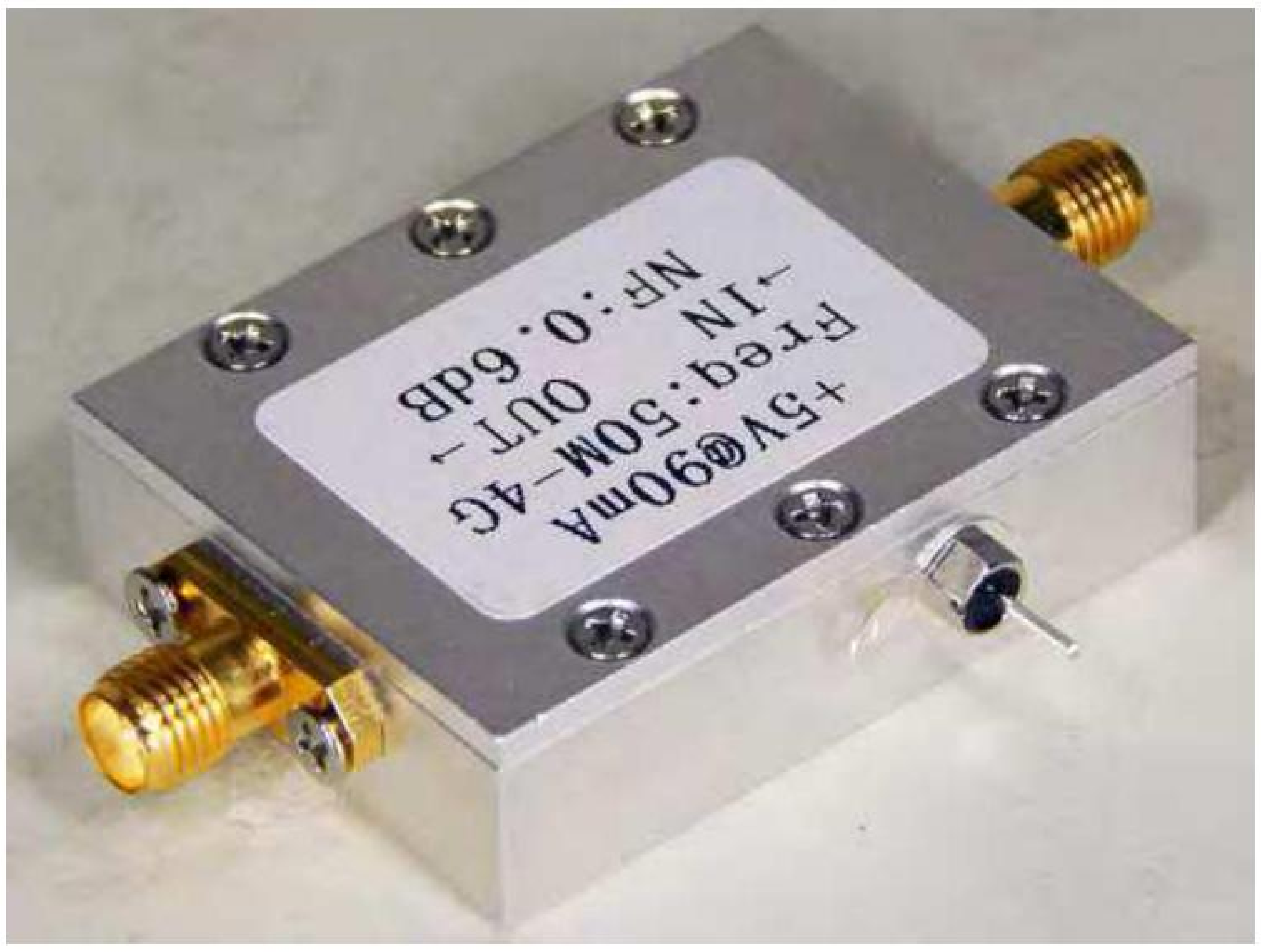
First, I inserted the amplifier modules in front of the LTDZ analyser, with their inputs terminated with 50Ω, and ran some plots to see if their noise affected its noise floor. They did not; the noise floor measured –77dBm with or without both amplifiers.

The next set of tests involved feeding a –80dBm CW signal from my signal generator through the relevant amplifier module and into the LTDZ analyser at four frequencies: 1GHz, 2GHz, 3GHz and 4GHz. Without the amplifier, I would expect a flat line at –77dBm. Any peaks above this would mean that the amplifier was providing some benefit.

With the second (cheaper) module, I saw two bumps of about 7.5dB on either side of 1GHz in the first test, about 7dB on either side of 2GHz, about 4dB on either side of 3GHz, and about 2.5dB on either side of 4GHz. So this module does give the LTDZ analyser a modest increase in sensitivity up to 4GHz, without affecting its noise floor.

The reason why there were two bumps rather than one peak is explained in the main body of the article linked above. It's a property of the analyser's unnecessarily broad resolution bandwidth, not a failing of the amplifier module.

I also tested the more expensive LNA and got two bumps about 8dB high on either side of 1GHz, two much smaller bumps (<1dB) on either side of 2GHz, two similarly small bumps on either side of 3GHz, and no discernible bumps at all around 4GHz.



The third and last amplifier module is housed inside a cast aluminium case. There's an insulated pin fitted to the edge of the case which is used for power, along with a solder lug adjacent for the negative power lead.

I must conclude then that the second, less-expensive amplifier module with a stated frequency range of 5MHz to 6GHz is the best option for improving the sensitivity of the LTDZ analyser, and does give a helpful improvement in sensitivity, of about 10.5dB at 1GHz, 10dB at 2GHz, 7dB at 3GHz and 6.5dB at 4GHz.

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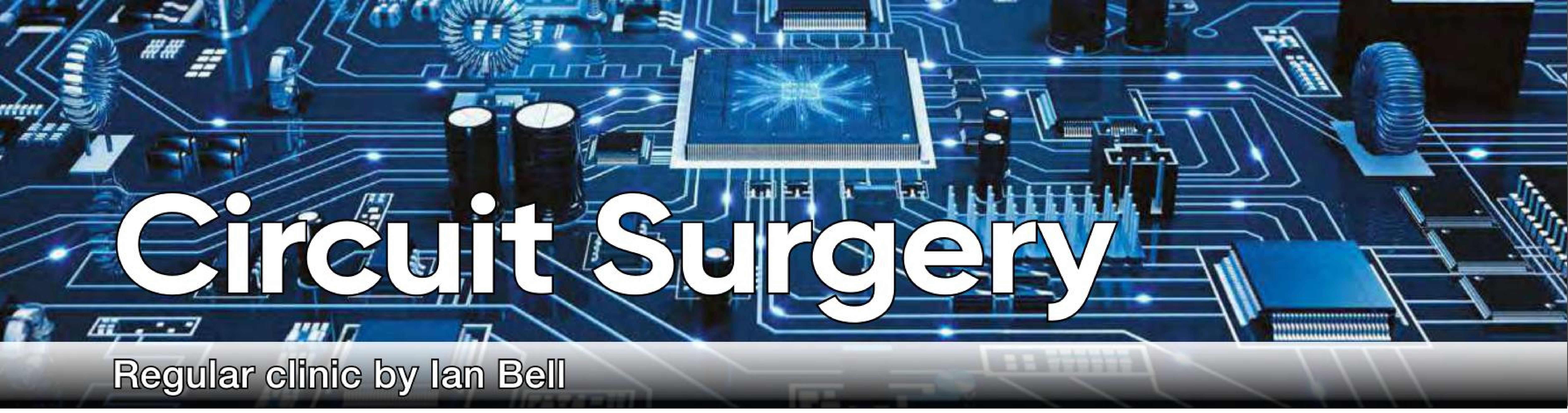


Circuit Surgery

Regular clinic by Ian Bell

Electronically controlled resistance – Part 8

This month, we conclude our series on electronically controlled resistance with a look at using digipots to control active filter circuits. Like previous articles, we will discuss general circuit design issues and approaches to simulation using LTspice. Filters are a large and complex area of electronics, so we will start with some general background before discussing digipot circuits.

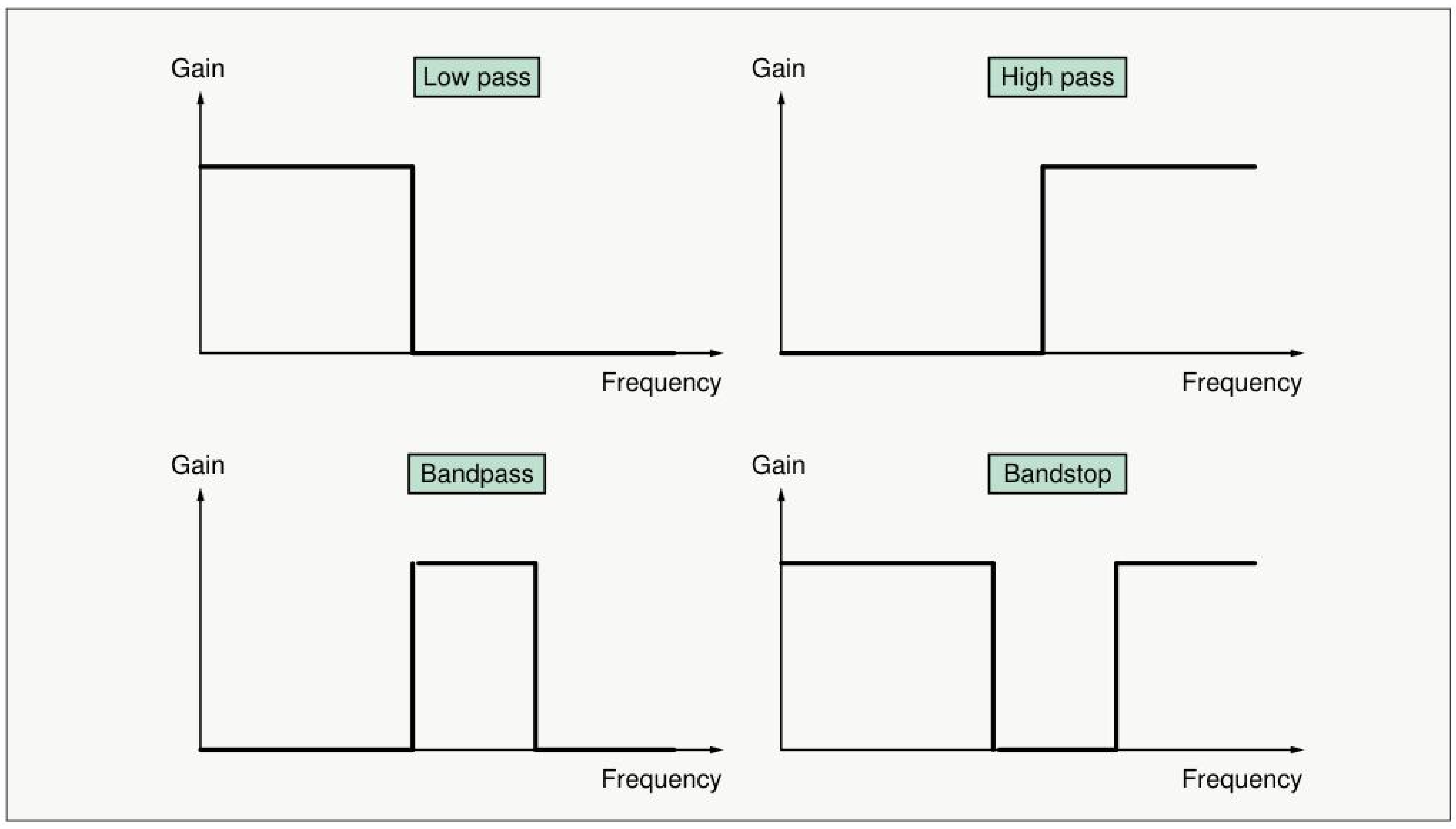


Fig.1. Basic filter bandforms.

Filter basics

A filter is a circuit which passes certain frequencies and rejects others. That is, the gain is designed to be relatively high over a range of wanted frequencies (the passband) and low for frequencies outside this range (the stopband). There are four basic classes of filter, referred to as 'bandforms', which are shown in idealised form in Fig.1. These are graphs of the filter's frequency response – that is, plots of gain versus frequency. Low-pass filters let low frequencies through and block high frequencies. High-pass filters let high frequencies through and block low frequencies. Bandpass filters let a specific range of frequencies through. Bandstop filters reject a specific range of frequencies.

There are few other bandforms forms beyond these basic classes. A notch filter is a bandstop filter with a very narrow stopband, which can be useful for rejecting a specific unwanted frequency. A comb filter has multiple, regularly spaced stopbands and passbands. There are also 'all pass' filters which have constant gain, but a specific phase shift response with frequency.

The idealised (so-called 'brick wall') filters in Fig.1 cannot be implemented – it is not possible to have an infinitely fast transition from passband to stopband in a real circuit, so the transition occurs over a range of frequencies. Furthermore, the gain in the passband may not be constant (as it is implied by Fig.1) and the stopband gain will not be either zero (complete rejection) or constant at some low level. Fig.2 shows a low-pass response with various features that occur in real circuits.

On filter response plots the gain or attenuation is usually expressed in decibels, which is a logarithmic scale. For voltage gain A the value (in decibels,dB) is given by: $20 \times \log_{10}(A)$. The (horizontal) frequency axis of the graph is also usually logarithmic, with the scale marked in multiple-of-ten steps, referred to as 'decades'.

Response types

There are various filter response types available named after their related mathematics, such as Butterworth, Bessel and Chebyshev filters. The features shown in Fig.2 vary with different response types and there is a trade-off in terms of desirable features. For example, Butterworth filters have maximally flat passbands with a relatively slow change of gain near the cut-off, while Chebyshev filters have significant passband ripple, but their gain decreases more rapidly near the cut-off.

For an ideal filter, the transition from passband to stopband occurs at a single frequency. For real filters the transition from passband to stopband occurs over a range of frequencies so we need to specify exactly what we mean by 'cut-off frequency'. For a flat passband the cut-off is often defined as the frequency where the filter's gain is –3dB with respect to the passband gain. This is the point where the output signal has half the power it has in the passband. For filters with ripple, the cut-off frequency is usually defined as the frequency where the response has dropped by an amount equal to the ripple size relative to the maximum passband gain (as seen in Fig.2).

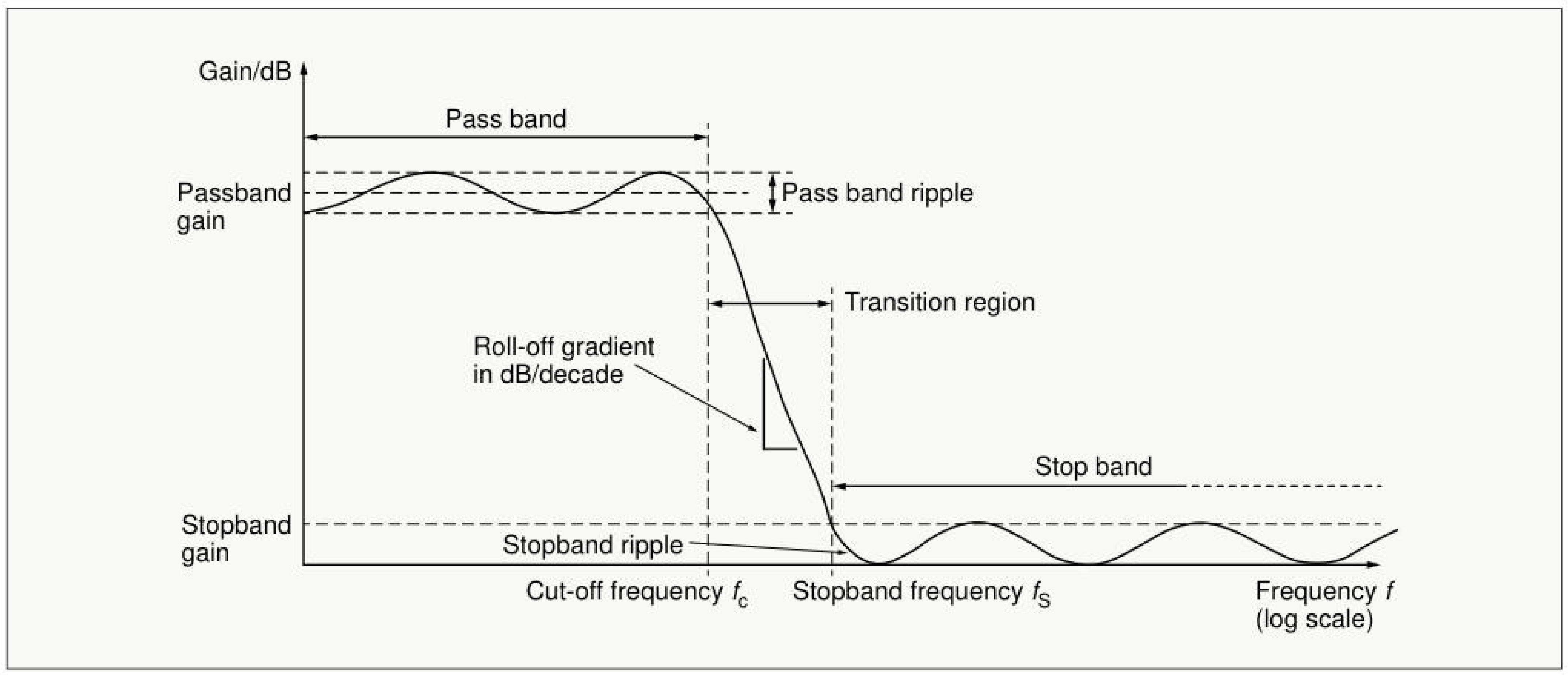


Fig.2. Features of filter frequency response curves.

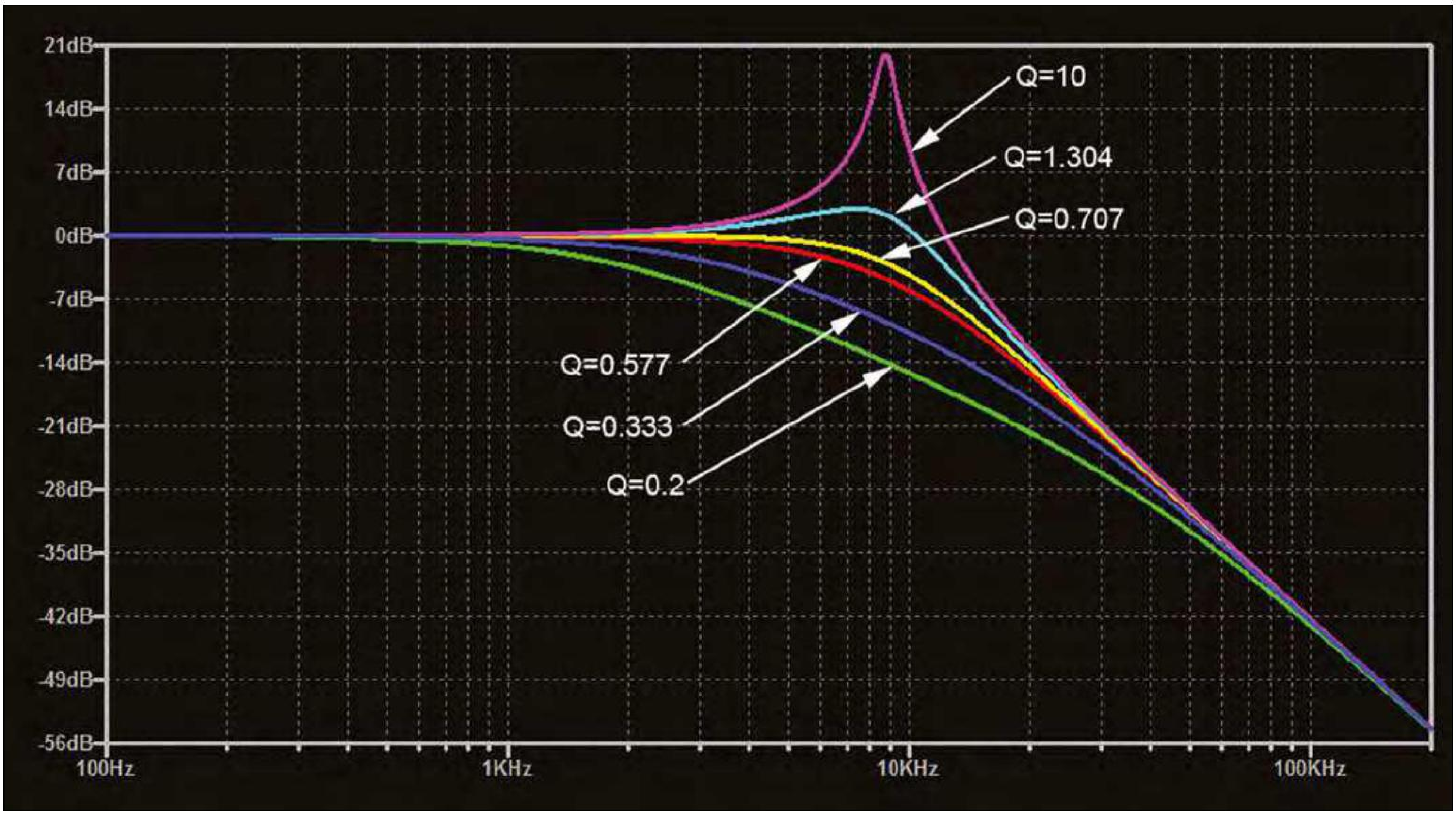


Fig.3. Low-pass response for various Q values.

The slope of the frequency response in the transition region/stopband (see Fig.2) indicates how quickly the filter's gain drops as the frequency moves away from cut-off. For many filters, at frequencies well into the transition region/stopband, the response tends to decrease as a straight line when plotted on a graph of decibels against log frequency. The slope is measured in dB per decade and is called the 'roll-off'. The roll-off may be different (and changing) near the cut-off, but the term usually refers to ultimate roll-off, at a frequency sufficiently far from the cut-off.

The ultimate roll-off is determined by the order of the filter, the higher the order the faster the falloff. A single RC filter is first order and rolls off at 20dB/decade, while an N-th order filter rolls off at $20 \times N$ dB/decade. The order of the filter determines the ultimate roll-off, but the response type (Butterworth, Chebyshev and so on.) determines the shape of the response near the cut-off.

Q – quality factor

The Q, or 'quality factor', of a filter determines the response type (shape). Fig.3 shows the response of several second-order low-pass filters with different Q values. The responses are the same at frequencies a long way from cut-off (both high and low) but are very different around the cut-off point.

For bandpass filters, Q is the ratio of bandwidth relative to centre frequency. If a band-pass filter has a centre frequency of f_0 and a bandwidth of f_b the Q factor is given by $Q = f_0/f_b$. High-Q bandpass and bandstop filters are often required in radio circuits.

For low-pass filters we typically require relatively low Q values because higher Q values result in a sharp peak around the cut-off frequency (see Fig.3). Usually, we would not want this peak to be very high. The situation is the same for high-pass filters. For these filters the damping factor ($\zeta = 1/(2Q)$) is often used instead of Q as it is perhaps more intuitive However, the reciprocal relationship means they are fundamentally the same thing. Higher damping results in a slower, smoother transition from passband to stopband.

The properties of filters are related to resonance – the tendency of some systems to respond at greater amplitude when applied oscillations match the system's natural frequency of vibration. The peaks seen in Fig.3 occur at the resonant frequency. The resonant frequency is a 'natural' property of the filter, or to put it another way, fundamentally related to the mathematics of the filter's function. The cut-off frequency is effectively arbitrarily defined, so they are not the same thing.

Frequency scaling factor

For a particular response type, order and definition of cut-off frequency (f_c) there will be a fixed relationship between the resonant frequency (f_0) and cut-off frequency, which can be expressed as a frequency scaling factor (F_s), such that:

$$f_0 = F_s f_c$$

The scaling factors are typically, but not always, in the range 0.2 to 2. For Butterworth filters with the cut-off defined as –3dB, the frequency scaling factor is 1.

We have discussed frequency response in detail, but filters are also characterised in terms of their phase response (how phase shift varies with frequency). Phase shift is a measure of delay relative to the cycle time at the frequency of interest and ideally increases linearly with frequency – this implies that the absolute delay time is equal at all frequencies. Different filter types have different phase responses. As well as the variation of gain and phase with frequency, the time-domain response of filters is important. Typically, this is characterised by looking at the response to a step change in the input voltage. Again, this depends on the order and response type and there are trade-offs in desirable properties.

Filter circuit design

There are many different circuits which can be configured to implement a desired filter response (for example Sallen-Key, multiple feedback and state variable). These have different non-ideal characteristics which might need to be taken into consideration and balanced against factors such as cost and complexity. When designing a filter, the bandform and cut off frequency are usually straightforward to determine from the application. The order, response type (Butterworth, Chebyshev) and circuit implementation choices will be based on the performance requirements – for example, how close are unwanted signals

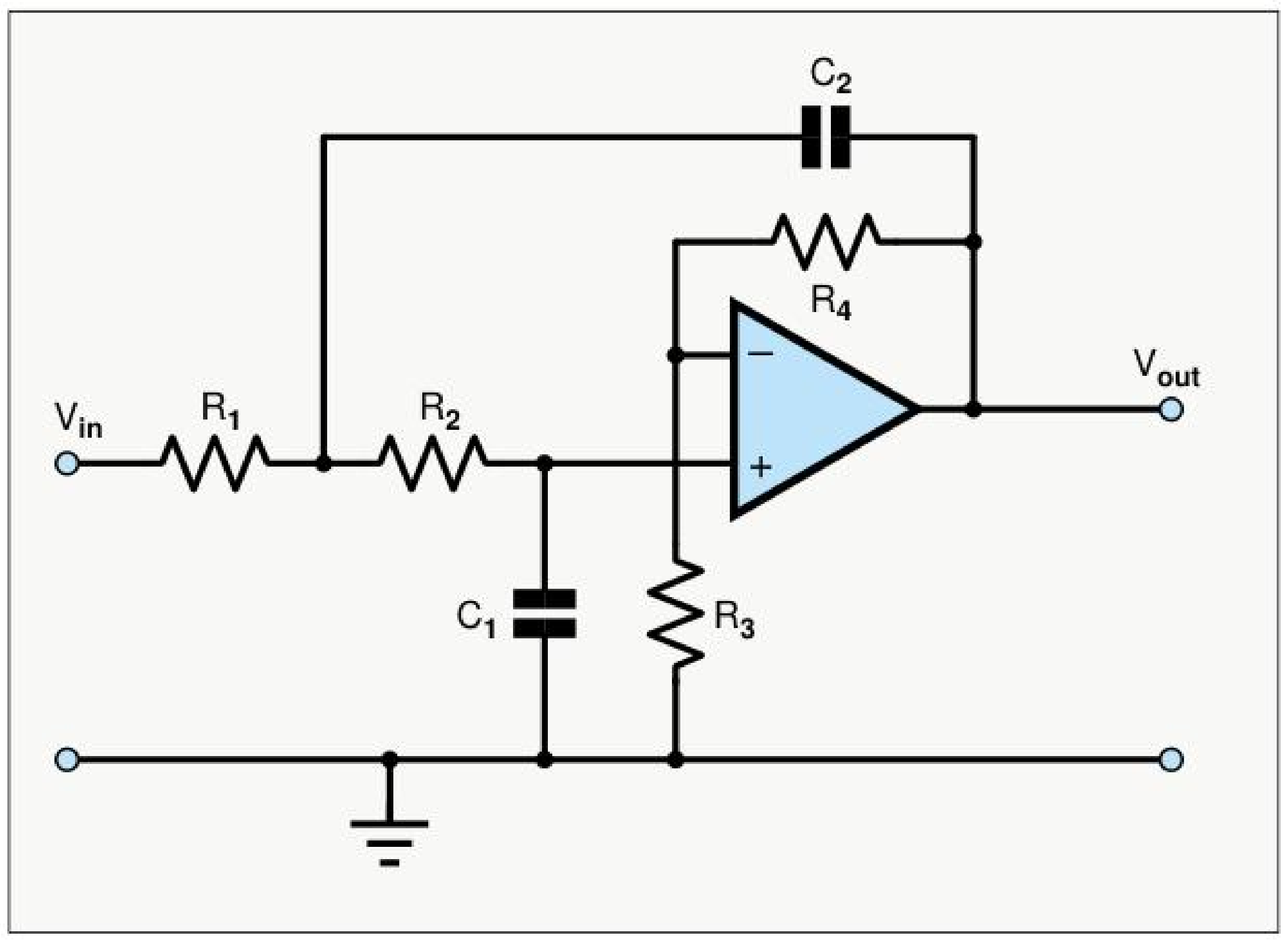
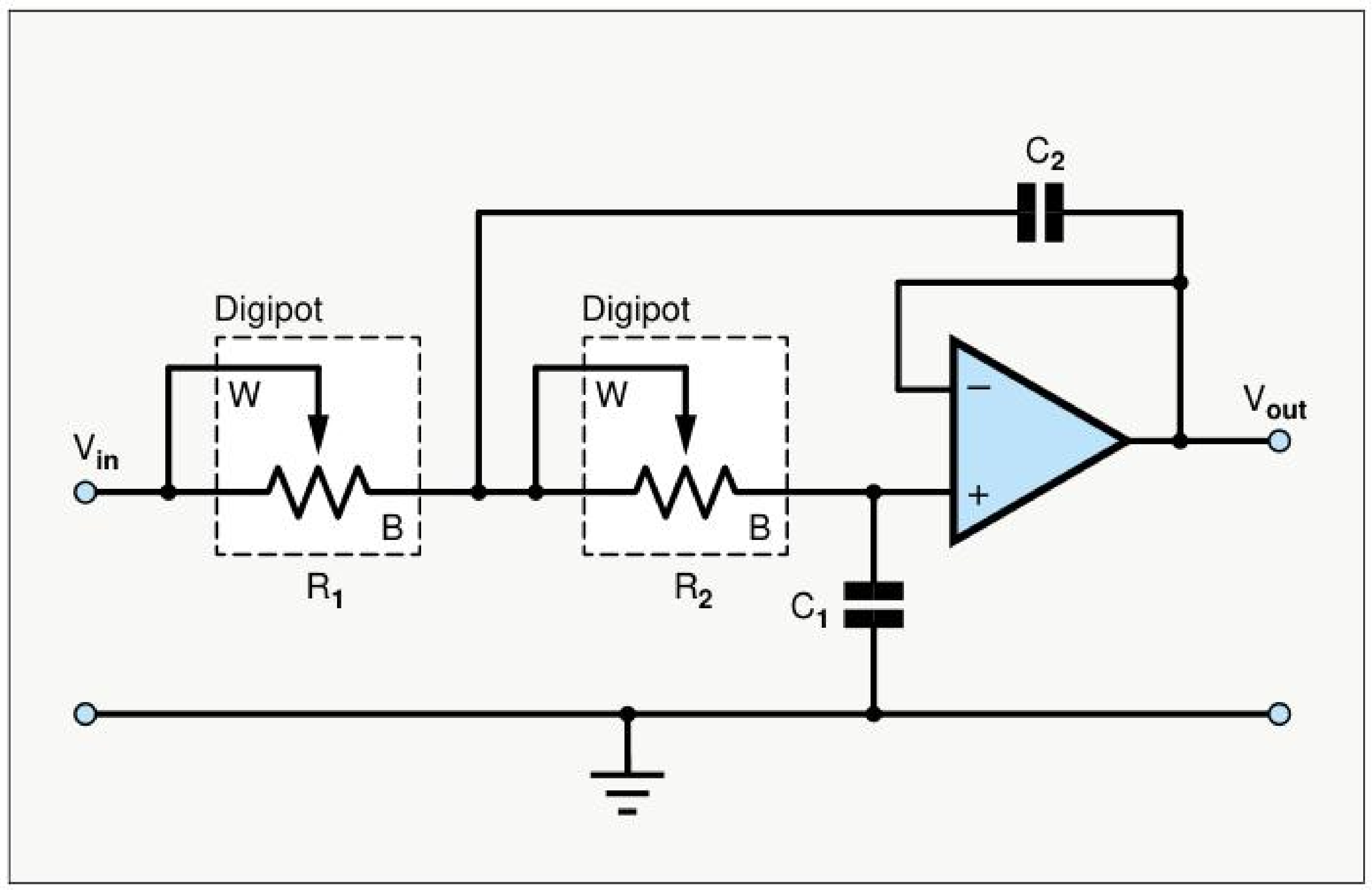


Fig.4. (left) Sallen-Key second-order low-pass filter.

Fig.5. (right) Unity-gain Sallen-Key low-pass filter with digipot cut-off frequency control.



to wanted ones and how much do they need to be attenuated.

For the various circuit implementations there are equations relating the component values to the resonant frequency and Q. The required response type determines the Q and frequency-scaling factor. These can be found in filter design tables published in various places. A well-known example of this is the *Active Filter Cookbook* by Don Lancaster, which was first published in 1975 and is described as the best-selling book on active filter design. Another source is *Active Low-Pass Filter Design*, an application note by Jim Karki from Texas Instruments (SLOA049 – see: **https://bit.ly/pe-apr23-ti**). An alternative to table-assisted manual calculations is to use a filter design app or online tool. These make things easy but may restrict the options for exactly how the filter is implemented.

Filters represent a huge 'design space' of possibilities – bandform, response type, order, circuit implementation and so on. To keep things manageable for the remainder of this article on using digipots with filters we will just look at second-order low-pass Sallen-Key Filters. Sallen-Key filters are widely used, and tools are available to help design them (select the required component values). Low-pass filters are commonly required in microcontroller circuits for anti-aliasing and reconstruction filters before/after ADCs and DACs, where cut-off frequency programmability may be desirable.

Sallen-Key low-pass filter

Fig.4 shows a Sallen-Key low-pass filter. It comprises a frequency-dependent circuit formed by R_1, R_2, C_1 and C_2, and a non-inverting op amp amplifier. The amplifier gain (A) is set by R_3 and R_4, and is given by:

$$A = 1 + \frac{R_4}{R_3}$$

The frequency-dependent circuit is similar to a two-stage RC filter, but with C_2 connected to positive feedback from the amplifier, rather than to ground. This allows the circuit to have much higher Q values than can be obtained with the RC filter, which has a maximum Q of 0.5, and is often lower.

The other design equations for this circuit are:

$$f_0 = \frac{1}{2\pi\sqrt{R_1R_2C_1C_1}}$$

$$Q = \frac{\sqrt{R_1R_2C_1C_1}}{R_1C_1 + R_2C_1 + R_1C_2(1 - A)}$$

Where f_0 is the resonant frequency. These equations are quite cumbersome, so simplifications are often made, which we will discuss below.

Digipots with Sallen-Key filters

To use the Sallen-Key with digipot control we need to be able to control the cut-off frequency just by varying the resistors. The capacitors should be chosen based on the midpoint of the required frequency control range. The resonant and hence cut-off frequency is set by R_1 and R_2, which need to be independently controlled, which implies use of two digipots in rheostat mode. As we have discussed previously, digipot resistance values are often not particularly accurate, which will affect the accuracy with which the cut-off frequency can be controlled. Use of a dual digipot device would usually be a good option.

We are probably less likely to want to control the Q with a digipot – in most cases the requirement would be for a fixed response shape with a variable cut-off frequency. However, it would be possible to use a digipot to set the amplifier gain (via R_3 and R_4) and hence make Q programmable. We discussed use of digipots to control op amp amplifier gain in *Part 5*.

Use of digipots may introduce limitations on the filter design. For example, their parasitic capacitance is likely to be higher than the same filter using fixed resistors. Parasitic capacitance is the unwanted capacitance inherent in structure of the pins and circuitry of the digipot device. This will limit the upper frequencies than can be used or accurately controlled. Frequency-setting capacitors should dominate the digipot parasitics, so something around 10nF may be the smallest capacitor value that should be used, but for a real design the details of individual digipot devices can be checked on datasheets.

Sallen-Key simplifications

One approach to simplifying the Sallen-Key equations is to use equal component values $R = R_1 = R_2$, and $C = C_1 = C_2$, which gives:

$$F_Sf_c = f_0 = \frac{1}{2\pi RC}$$

$$Q = \frac{1}{3 - A}$$

This provides very simple design equations but does not allow the overall gain of the filter to be set independently of the Q value. The circuit can be designed by choosing a required response, which sets the Q, and choosing R_3 and R_4 to obtain the gain required (A) for that Q. The Q could be set independently of the frequency with a digipot, as mentioned above, but the gain variation may need to be compensated for by another variable gain stage. The frequency is set by choosing C and controlling R with two digipots in rheostat mode set to the same resistance to set the resonant frequency. The resonant frequency is calculated from the required cut-off frequency using the frequency-scaling factor.

The gain variations discussed above can be avoided by using a fixed gain. This requires at least the two resistors or the two capacitors to have different values. A commonly used variant of the Sallen-Key filter is the unity-gain version shown in Fig.5, which also shows how the digipots are used.

Another design simplification approach is to set equal resistors and capacitors with ratio n, that is $R = R_1 = R_2$, and $C_2 = nC_1$ which gives:

$$F_Sf_c = f_0 = \frac{1}{2\pi RC_1\sqrt{n}}$$

$$Q = \frac{\sqrt{n}}{2}$$

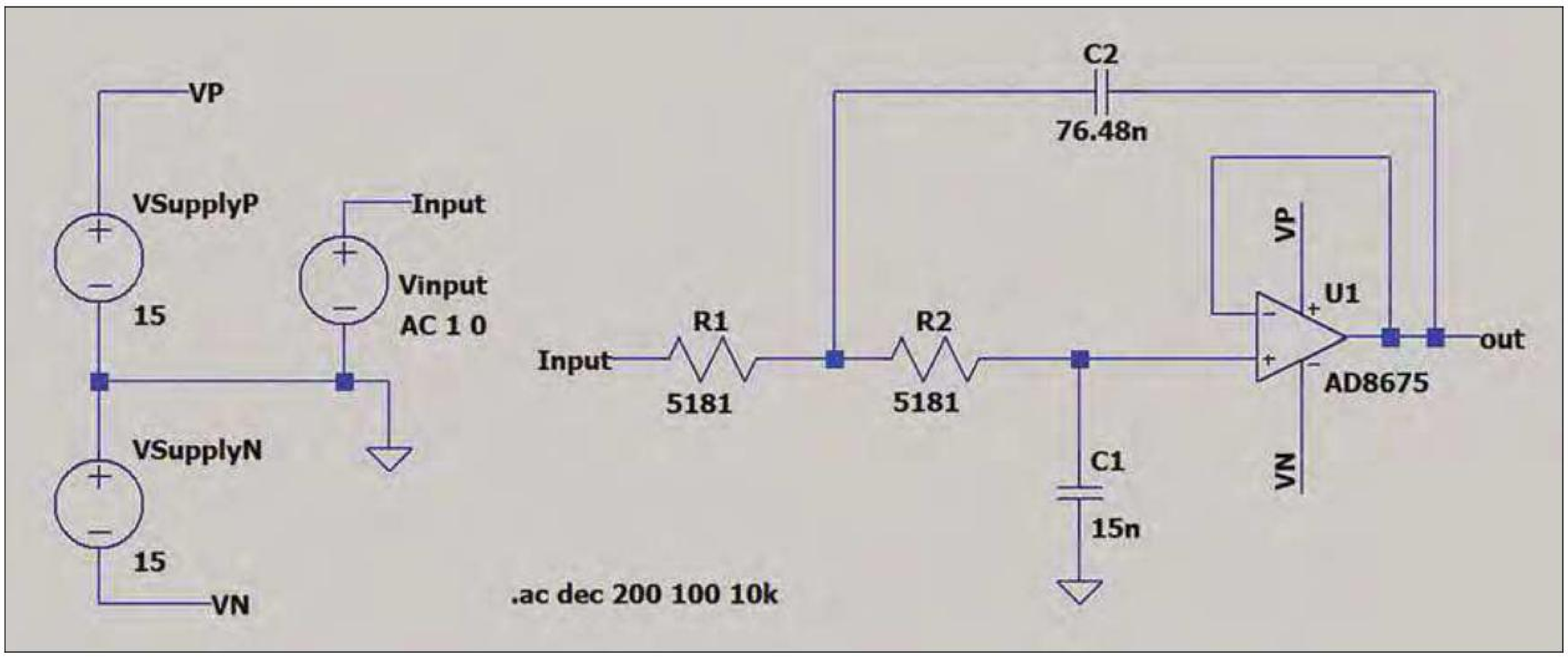


Fig.6. LTspice schematic for 1kHz unity-gain Sallen-Key low-pass filter.

To design with this approach the required response type sets the Q, which in turn sets the capacitor ratio (n). The base capacitance value, n and the calculated resonant frequency are used to set the resistor value.

Example design

Consider a filter of Chebyshev type with 2dB passband ripple and 1kHz cut-off. If we look it up, $Q = 1.129$ and $F_s = 0.907$ and using the equal-resistor unity-gain Sallen-Key circuit we need $n = 4Q^2 = 5.099$. Choosing $C_1 = 15\text{nF}$ gives $C_2 = 76.48\text{nF}$. For 1kHz cut-off we need $f_0 = F_s f_c = 0.852 \times 1000 = 852$. We can then calculate R as:

$$R = \frac{1}{2\pi f_0 C_1 \sqrt{n}}$$

$$= \frac{1}{2\pi \times 852 \times 15nF \ \times \sqrt{5.099}} = 5181$$

Fig.6 shows an LTspice schematic of the filter implementation. The simulation results (AC analysis to plot frequency response) for this circuit in Fig.7 show the gain is 0dB at low frequencies (unity gain). The gain peaks at +2dB (this is the 2dB passband ripple). The cut-off frequency for this type of filter is defined as the ripple size below the peak gain, which in this case is the point where it crosses 0dB as it transitions into the stopband. This occurs at 1kHz, as designed.

Setting the digipot code

In a typical programmable filter application, there are likely to be a set of required cut-of frequencies. For these cut-off frequencies to be implemented in a circuit like that in Fig.5 the required resistor values must fall within the range of resistance values available from the digipot, combined with fixed capacitor values. This means that very wide frequency ranges will not be possible, but something from 10:1 to 100:1 should be possible.

The basic filter calculations discussed above determine the required resistance values, but these need to be mapped to the digipot codes giving the nearest resistance values. The exact resistance required may not be available from the digipot, leading to errors in the frequency setting. The more positions the digipot has the more likely the frequency can be set close to the desired value.

The reciprocal nature of the frequency to resistance relationship means that at higher frequencies (lower resistance) each step in resistance from one code to the next represents a larger frequency change. This in turn means that it is less likely that exactly the right resistance value will be available at the higher frequency end of the programmable range.

As discussed previously (see *Part 5* in *PE*, January 2023) digipots can be modelled as two resistors R_A and R_B such that the total resistance $R_A + R_B = R_{AB}$ where R_{AB} is the resistance between the terminals A and B and the specified resistance of the digipot. In rheostat mode we use just one of these resistances, say from terminal B to the wiper (as drawn in Fig.5). For a digipot with S steps we need a digital code D to set a resistance value R as follows:

$$D = S\frac{R}{R_{AB}}$$

The actual resistance obtained is:

$$R = R_{AB}\frac{D}{S}$$

In some cases, there may be a significant difference between the required and obtained resistance, in other cases they will be close. For example, to set a 10kΩ, 256-step digipot to 5181Ω (from the above example) requires a digital code of 256 × (10000 / 5181) = 133. The actual resistance is 5195Ω , an error of just 0.3%. For a 100kΩ, 256-step digipot the code required is 13 and the resistance is 5078Ω, a 2% error. Smaller resistances may produce larger errors with a given digipot. For example, 518.1Ω for a 10kHz cut-off with the above circuit requires codes 13 and 1 with resistance errors of 2% and 25% respectively for the 10kΩ and 100kΩ digipots. This assumes a perfectly accurate digipot, but the R_{AB} value itself may be subject to quite a large tolerance, for example 20% in some cases.

Design tools

The filter design calculations above, and the associated need to obtain the correct Q and frequency-scaling factor can be avoided by using a filter design app or online utility. These tools may reduce the options for component selection compared with manual

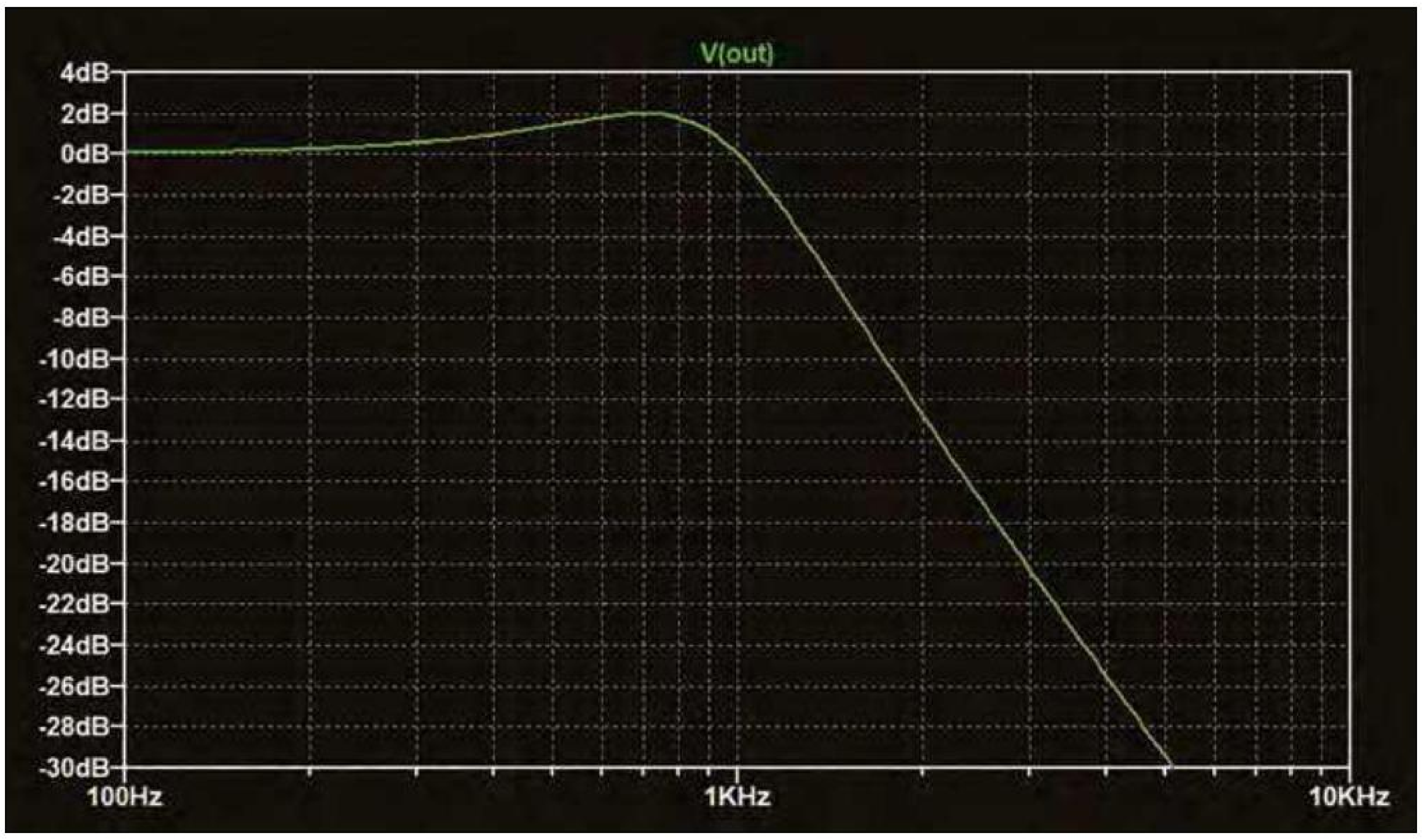
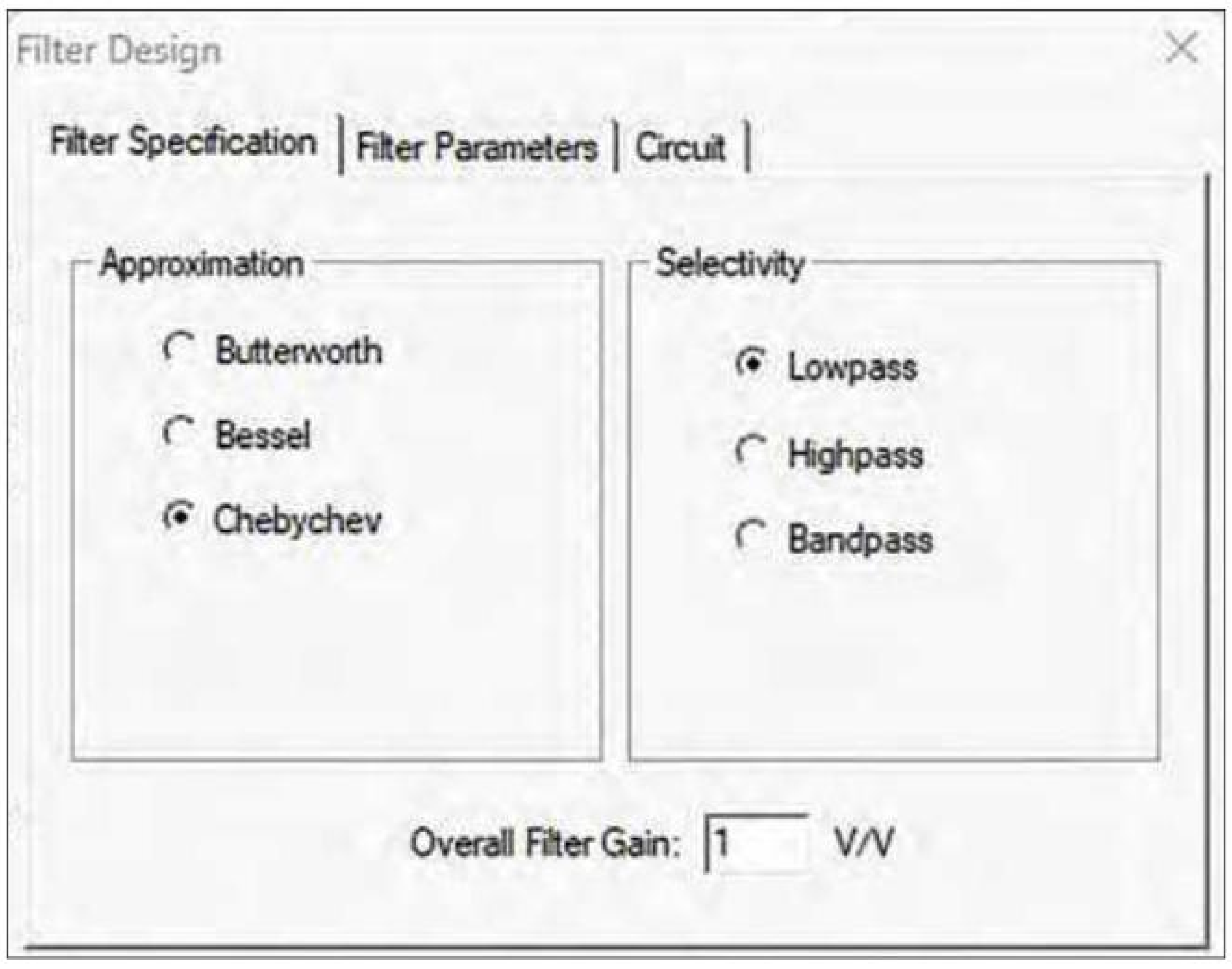


Fig.7. Simulation results for the circuit in Fig.6.


Filter Design

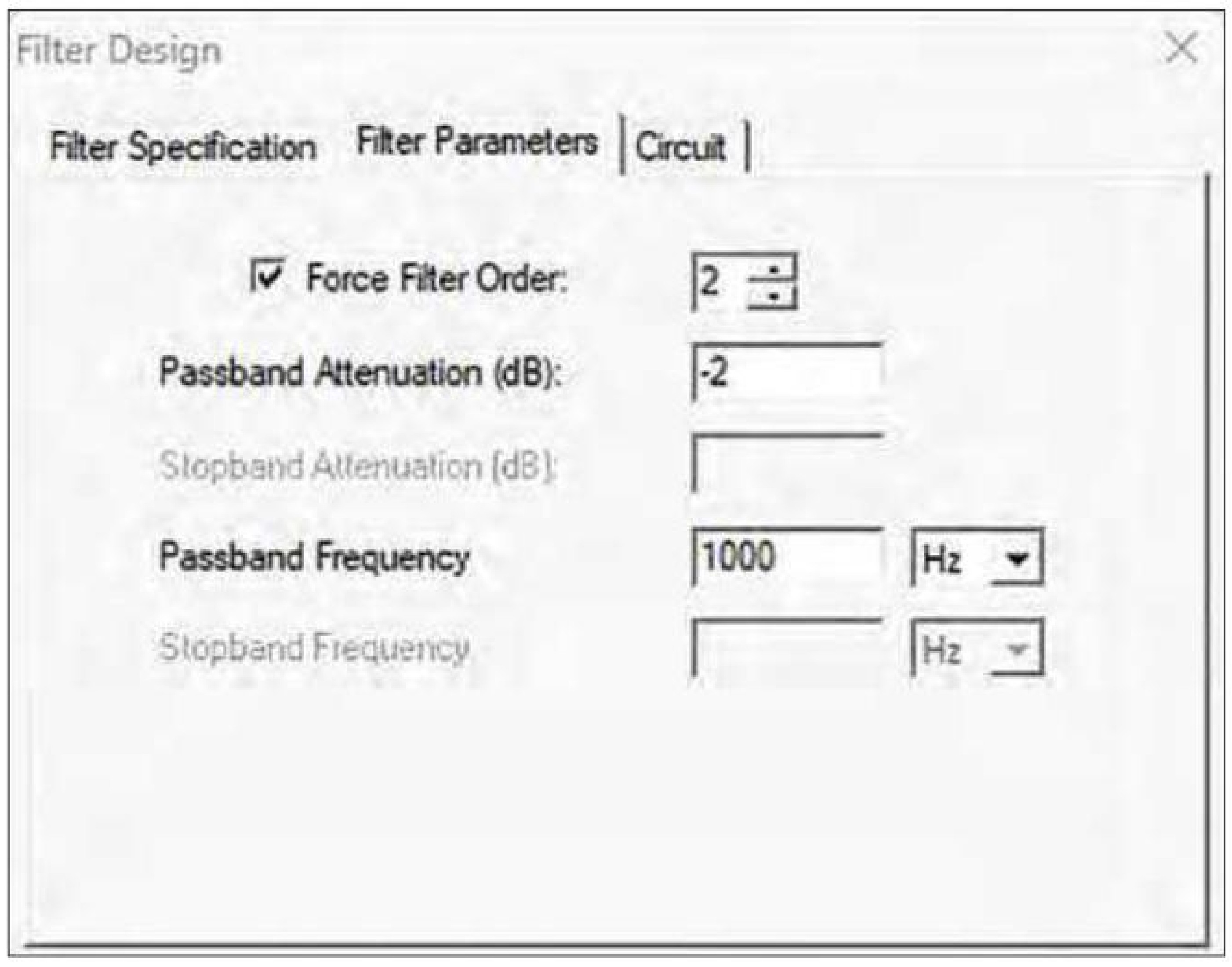
Filter Specification | Filter Parameters | Circuit

Approximation
○ Butterworth
○ Bessel
● Chebychev

Selectivity
● Lowpass
○ Highpass
○ Bandpass

Overall Filter Gain: 1 V/V

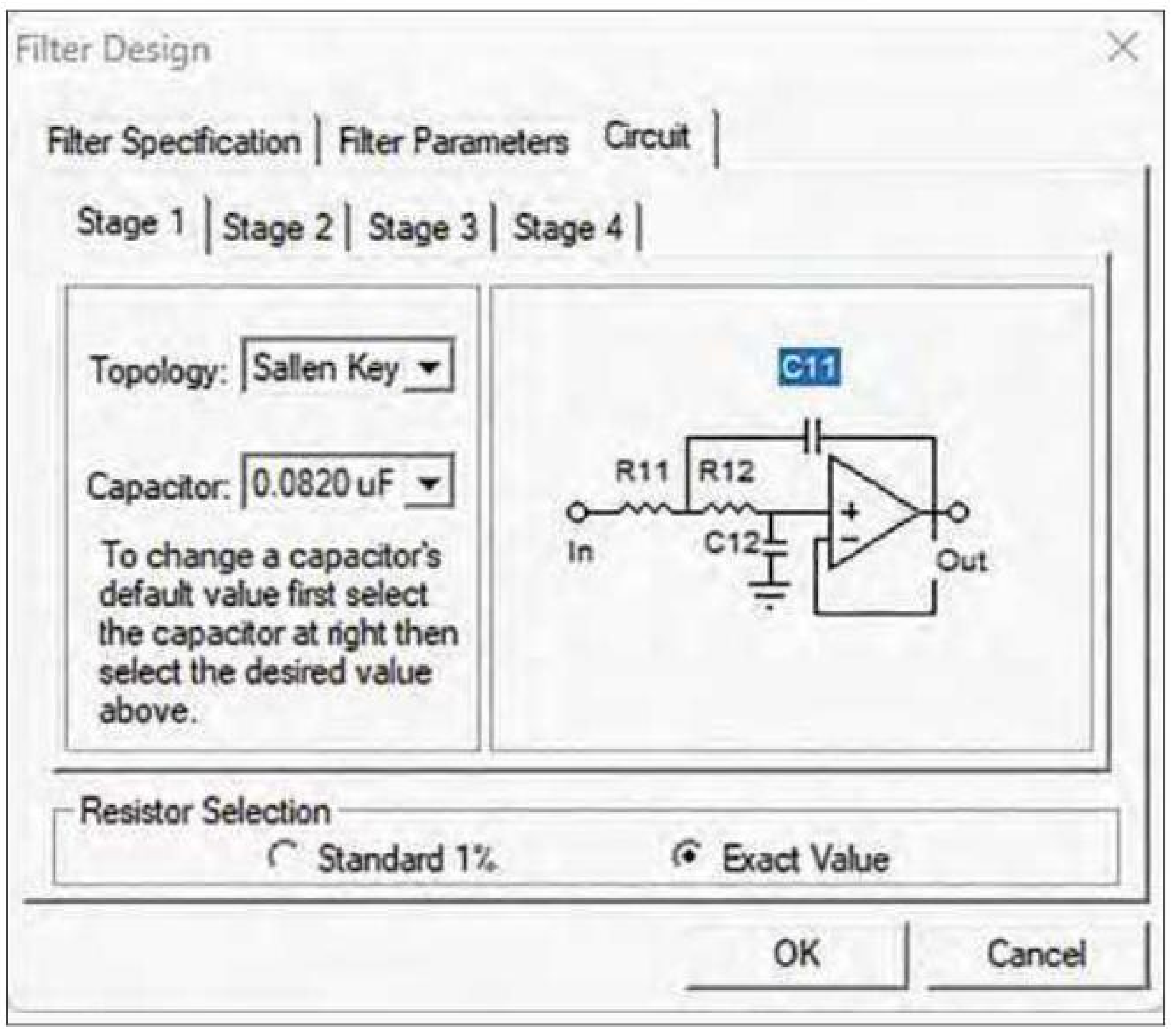
Fig.8. (left) FilterLab bandform and response type setting.


Filter Design

Filter Specification | Filter Parameters | Circuit

☑ Force Filter Order: 2
Passband Attenuation (dB): -2
Stopband Attenuation (dB):
Passband Frequency: 1000 Hz
Stopband Frequency: Hz

Fig.9. (right) FilterLab filter parameter settings.


Filter Design

Filter Specification | Filter Parameters | Circuit

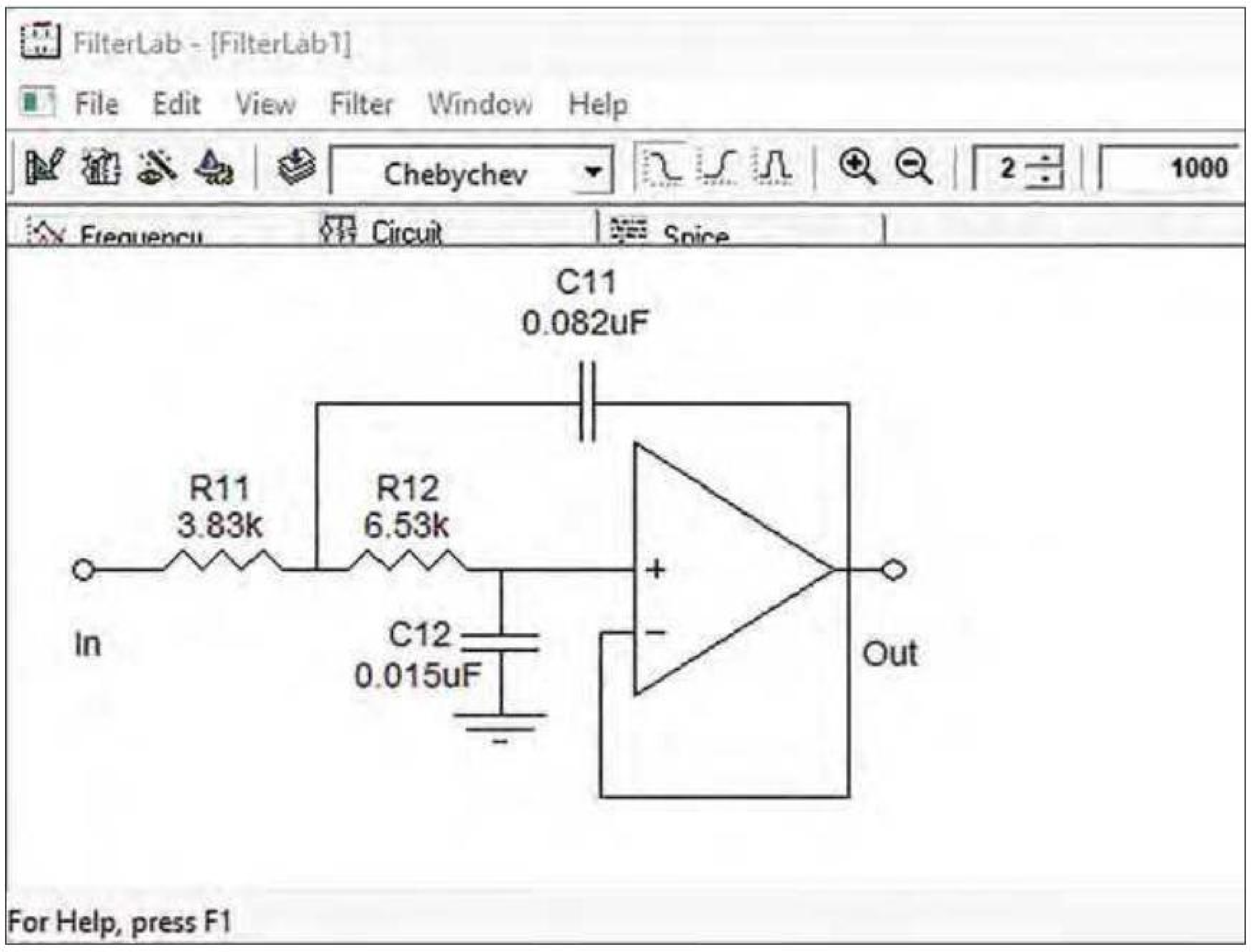
Stage 1 | Stage 2 | Stage 3 | Stage 4

Topology: Sallen Key

Capacitor: 0.0820 uF

To change a capacitor's default value first select the capacitor at right then select the desired value above.

Resistor Selection
○ Standard 1%
● Exact Value

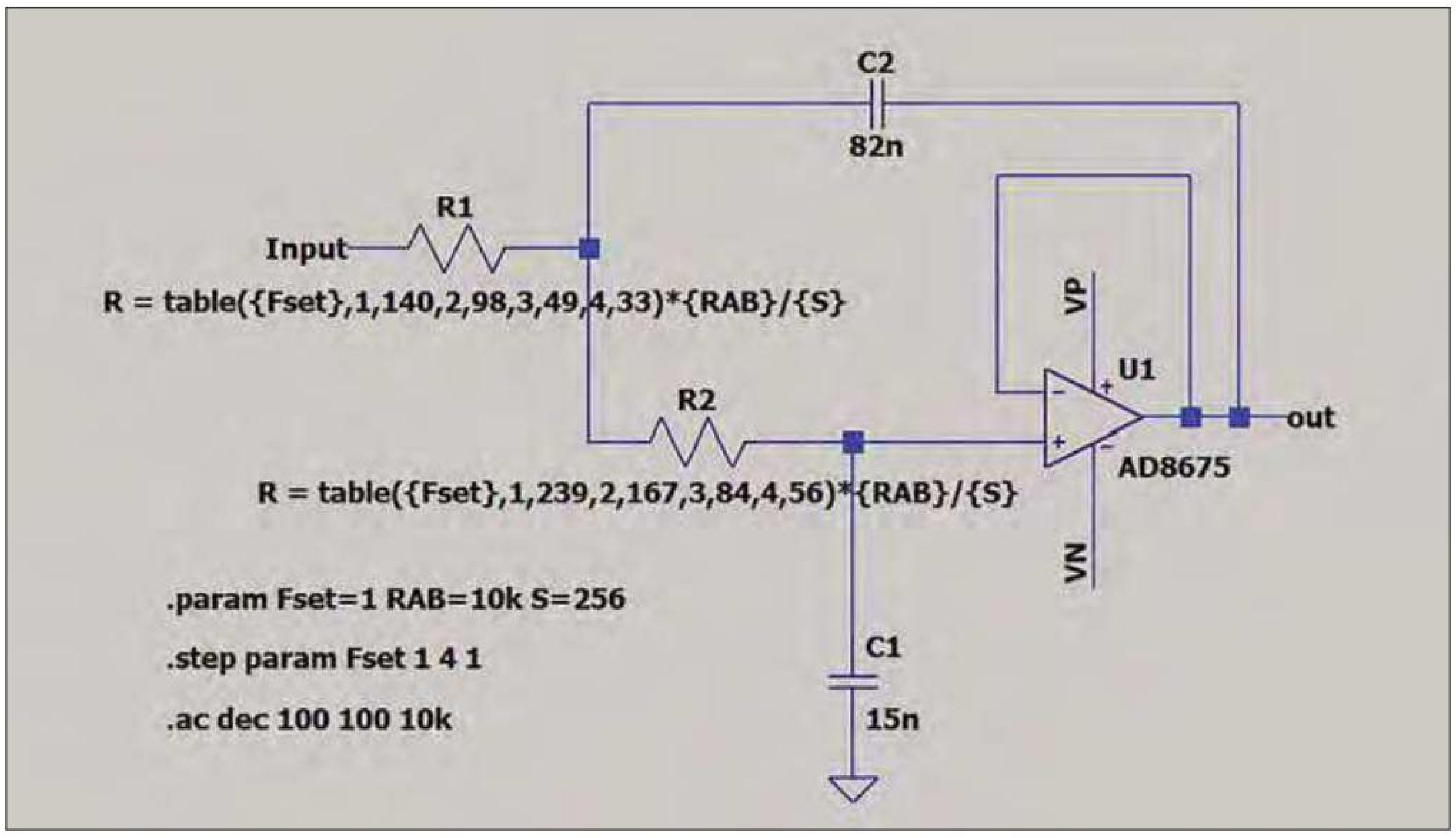

FilterLab - [FilterLab1]

For Help, press F1

Fig.10. (above) FilterLab circuit settings.
Fig.11. (right) Example FilterLab result.

design, which could be a problem in the context of digipot-controlled circuits. We need to be able to find a set of resistor values to set different cut-off frequencies using a circuit with the fixed capacitor values and op amp circuit gain. This means we have to be able to set the capacitor values and let the tool calculate the resistor values for a fixed-gain circuit such as the unity-gain Sallen-Key discussed above.

Unlike the simplified approach above, it is not necessary to have equal resistors. In fact, by using different resistor values (as calculated by the tool) the response shape can be changed as well as the cut-off frequency, allowing the shape as well as cut-off to be programmed. The way the numbers work means that if a range of response types is required the range of cut-off frequencies possible with a given digipot will be smaller than with a fixed response type.


C2
82n
R1
Input
R = table({Fset},1,140,2,98,3,49,4,33)*{RAB}/{S}
R2
R = table({Fset},1,239,2,167,3,84,4,56)*{RAB}/{S}
VP
U1
AD8675
VN
out
C1
15n

```
.param Fset=1 RAB=10k S=256
.step param Fset 1 4 1
.ac dec 100 100 10k
```

Fig.12. LTspice schematic for Sallen-Key filter with digipot control.

As was seen in the equal-resistor example design above, the capacitor ratio can influence the Q. The resistors do not have to be equal but similar values will make it easier to make use of a dual digipot. In general, the feedback capacitor (C_2 in Fig.5) will be larger than the capacitor at the op amp input (C_1). Unlike the above example, standard capacitor values should be used for a real design.

FilterLab

One filter design tool that allows you to set capacitor values is FilterLab from Microchip – see: **https://bit.ly/pe-apr23-mc**

To design a filter using this app, select Filter > Design from the menu and step through the three tabs in the dialog (see Fig.8 to Fig.10). The first tab is used to select the bandform and response type.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

Here we have selected Chebyshev lowpass as in the example above. The second tab sets the filter parameters, here we selected 'Force filter order' – this is to help make sure the tool uses the required circuit to implement the design. We select 1000Hz cut-off and –2dB for the passband to match the 2dB ripple Chebyshev design discussed above. The third tab allows the circuit type to be selected (Sallen-Key in this case) and the capacitor values to be set, so they are fixed in the circuit implementation. To do this, click on both capacitors and select the value from the dropdown list. The result is shown in Fig.12 – the schematic of the filter created by the app. For full details of using FilterLab consult the manual on the download page.

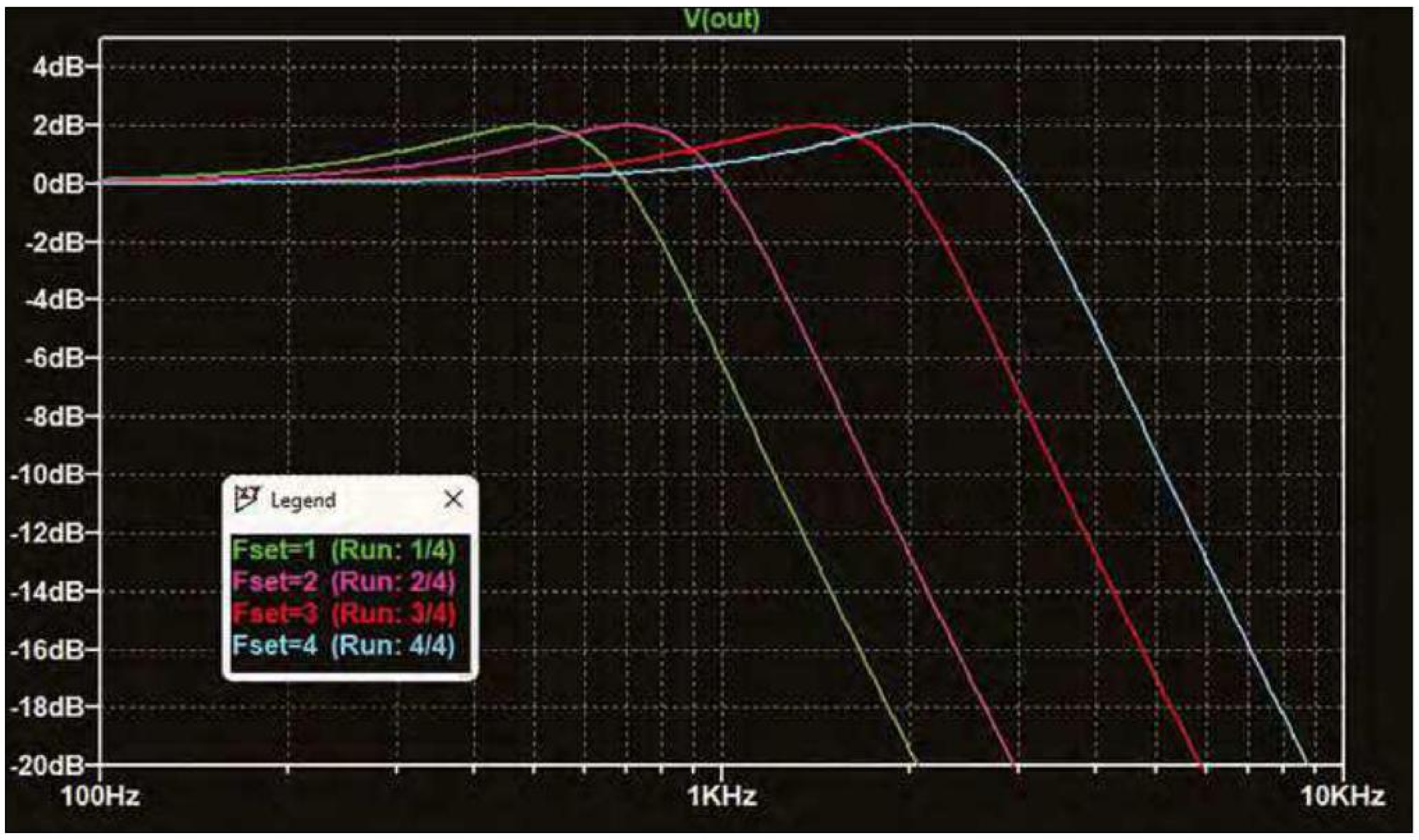


Fig.13. Simulation results from the circuit in Fig.12.

Example design

FilterLab was used to create three more circuits with different cut-offs. These can be simulated using the circuit in Fig.12. Using the procedure described above, digipot codes were calculated for a 256-step 10kΩ digipot for the following frequencies:

R_1 codes:	140	98	49	33
R_2 codes:	239	167	84	56
	700Hz	1kHz	2kHz	3kHz

In LTspice we can use a behavioural resistance (as used in previous parts) to calculate the actual digipot resistance using the formula above with the R_{AB} resistance and number of digipot steps as parameters (`RAB` and `S` respectively). To run through all the code combinations in one sweep simulation we can use the LTspice table function which uses an index to look up the corresponding value. For four configurations we need index values 1 to 4 which can be achieved by defining a parameter called `FSET` (frequency set), sweeping it in steps of 1 from 1 to 4 and using this in the look up. For example, for R_1:

```
.param Fset=1 RAB=100k N=256
R = table({Fset},1,140,2,98,3,49,4,33)*{RAB}/{S}
```

The results of the simulation are shown in Fig.13 and confirm that the filter responses are as designed.

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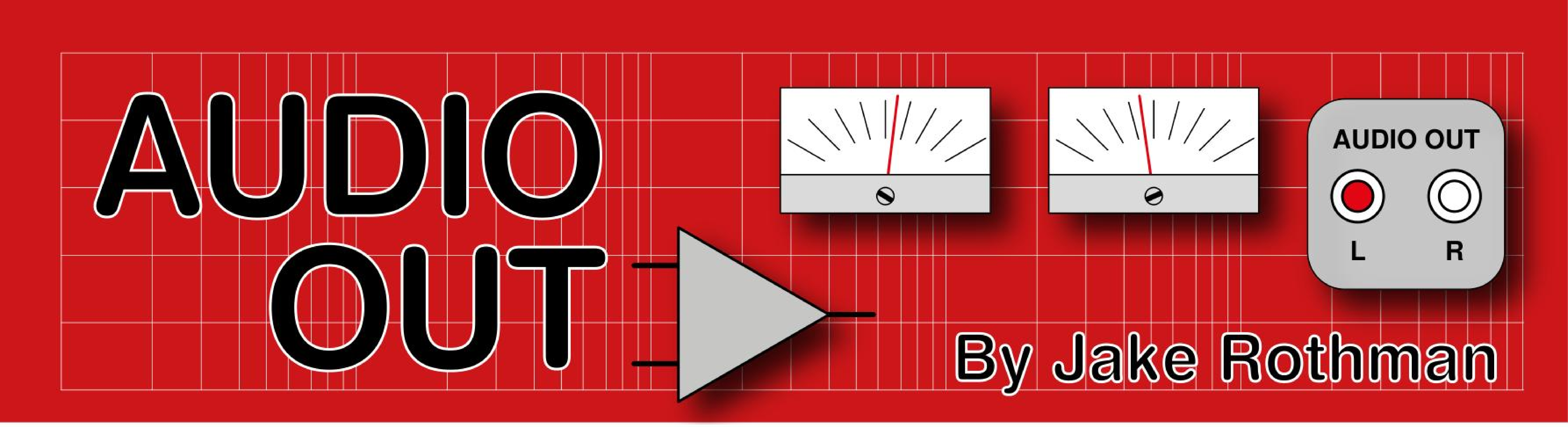
AUDIO OUT
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AUDIO OUT

By Jake Rothman

Universal op amp board (optimised for audio electronics) – Part 3 (dual op amp version)

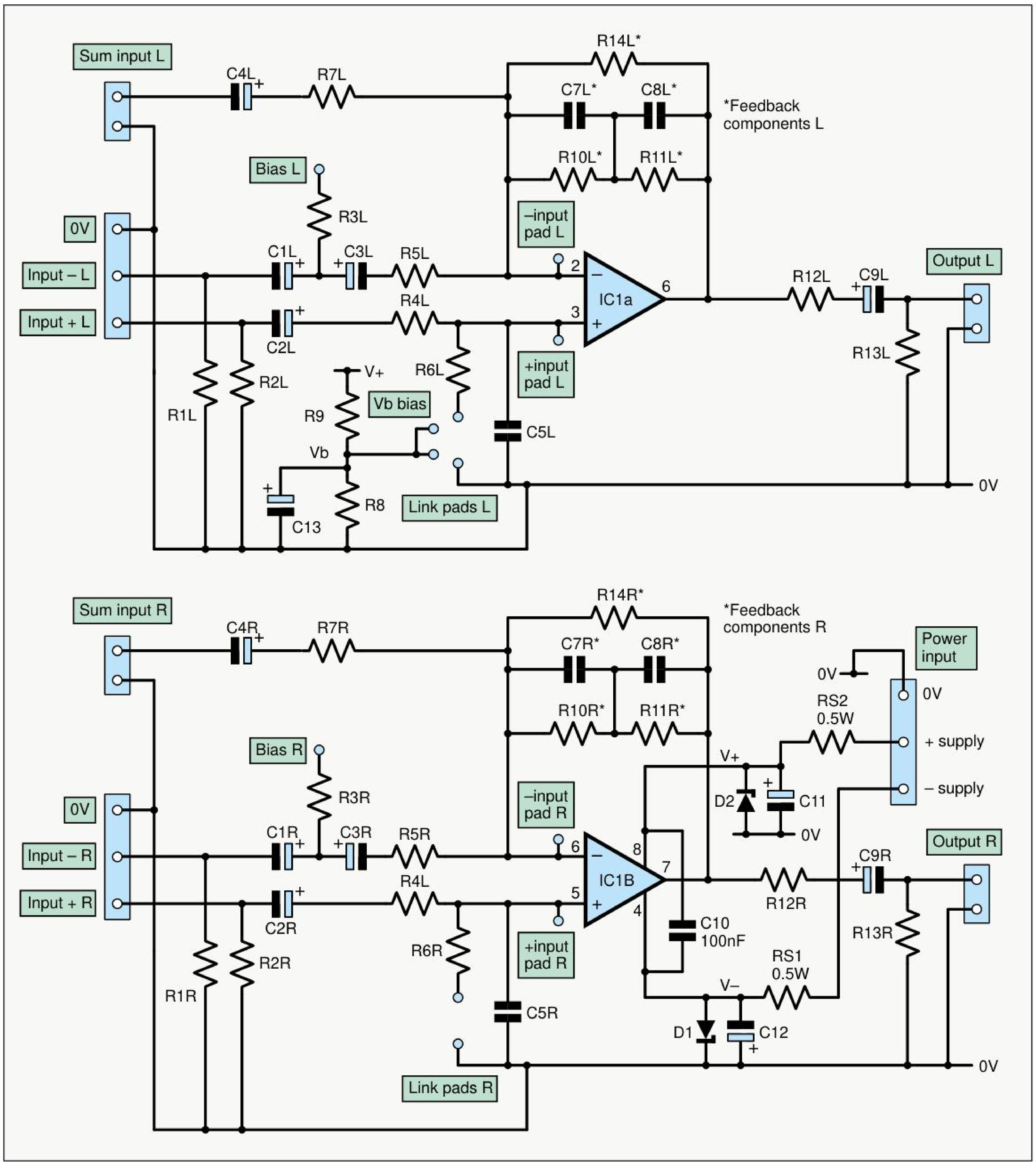

Sum input L
C4L
R7L
R14L*
C7L*
C8L*
*Feedback components L
R10L*
R11L*
Bias L
R3L
–input pad L
0V
Input – L
Input + L
C1L
C3L
R5L
R4L
C2L
2
3
IC1a
6
R12L
C9L
Output L
R13L
R1L
R2L
V+
R9
Vb bias
R6L
+input pad L
Vb
C5L
C13
R8
Link pads L
0V
Sum input R
C4R
R7R
R14R*
*Feedback components R
C7R*
C8R*
Power input
0V
RS2 0.5W
0V
+ supply
– supply
R10R*
R11R*
V+
Bias R
R3R
–input pad R
D2
C11
0V
0V
Input – R
Input + R
C1R
C3R
R5R
R4L
C2R
6
5
8
7
4
IC1B
C10 100nF
R12R
C9R
Output R
R13R
R2R
R1R
R6R
+input pad R
RS1 0.5W
V–
C5R
D1
C12
Link pads R
0V

Fig.29. Circuit diagram for the dual universal audio op amp PCB. This is virtually the same as the single circuit, bar a single bias network and some extra power supply zener regulators.

In the December 2022 and January 2023 issues of *PE* we described a universal board for single op amps. This month we'll introduce one for dual op amps which are more common and offer better value. The dual NE5532 for example, is half the price of its single counterpart, the NE5534, so you get four times as many op amps for the money. Also, one of the few op amps that's noticeably better for audio than the NE5532/4, the LM4652, only comes in a dual package.

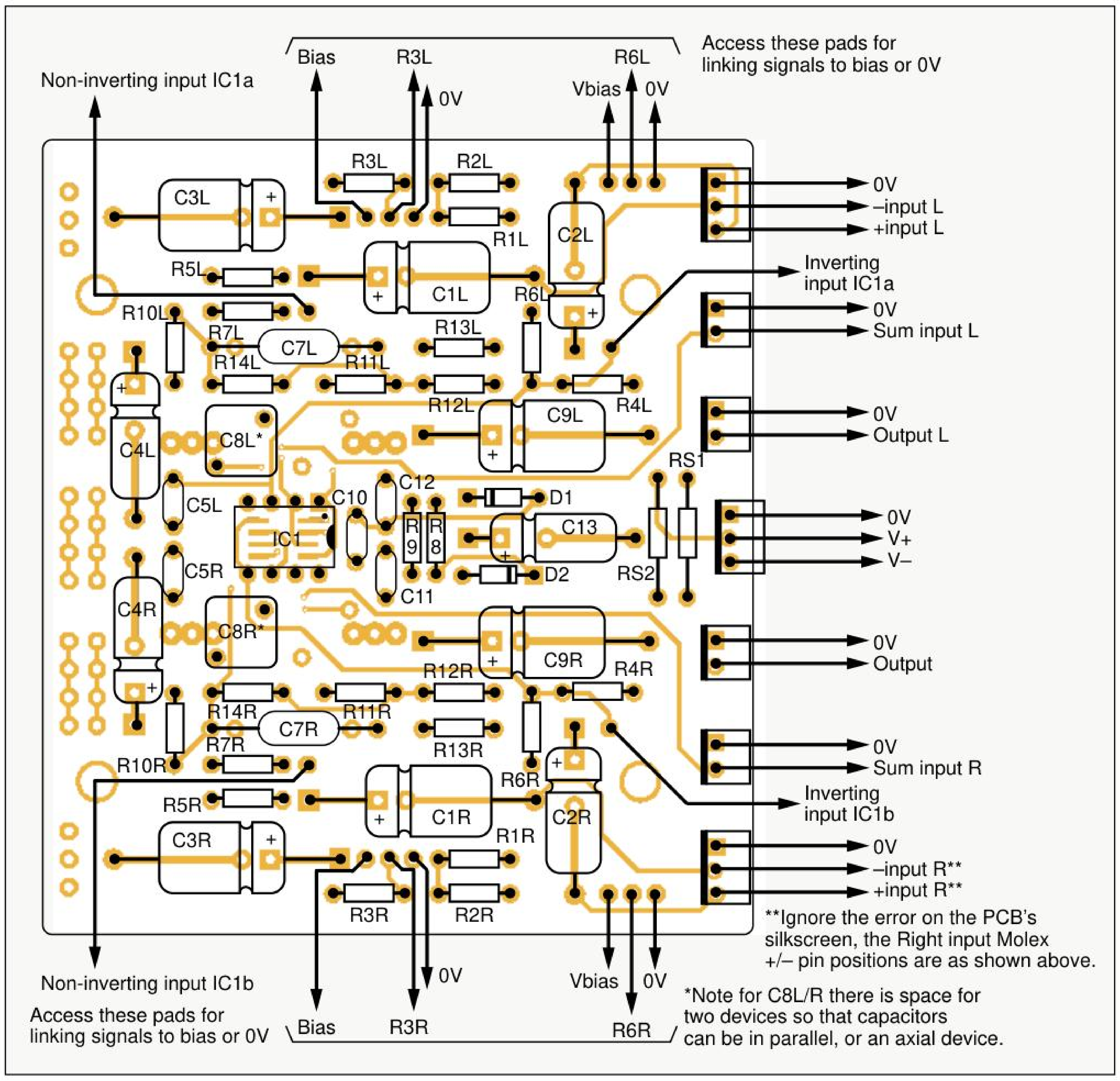
At the same time, PCB designer Mike Grindle and I decided to do a whole host of adapter boards for various op amp packages, which we'll come to next month.

Fearful symmetry

The general circuit of the dual board is the same as the single PCB (Fig.4 in *Part 1*) but duplicated, as shown in Fig.29. The dual chip (IC1a and IC1b) is shared between the left and right channels. This gave Mike an excuse to create a symmetrical mirror-imaged board. The overlay is shown in Fig.30. Most of the part numbering is the same – except for R4 and R5 which are swapped. The component numbers common to both channels are prefixed L and R. The half-rail bias components are renumbered R8, R9 and C13, since only one network is needed, shared between both channels. Finally, a dual-rail Zener regulator circuit is added to enable the board to be used with supply voltages higher than the op amps' maximum. This facility is useful if the board is to be supplied from say a power amplifier, where the rails are typically ±22V to ±60V. This situation commonly crops up where an amplifier needs the addition of balanced inputs, such as when converting a Hi-Fi amplifier for professional use.

Don't be deferential, go differential!

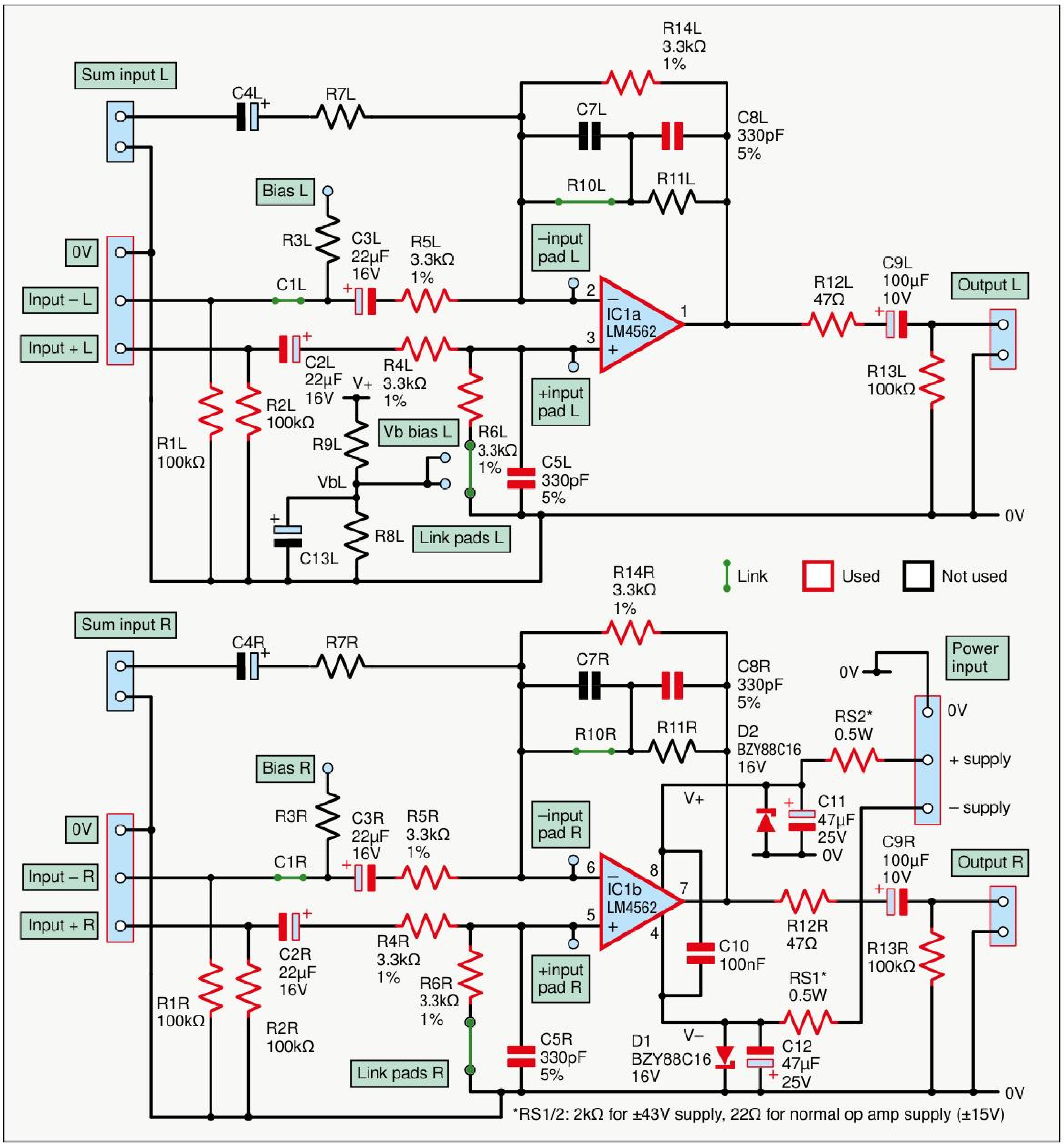
A suitable dual-channel differential amplifier to create balanced inputs is shown in Fig.31. The main differential amplifier resistors R4, R5, R6 and R14 are all 3.3kΩ. This gives a total


Non-inverting input IC1a
Bias
R3L
R6L
Vbias
0V
0V
Access these pads for linking signals to bias or 0V
C3L
R3L
R2L
R1L
C2L
0V
–input L
+input L
R5L
C1L
R6L
Inverting input IC1a
0V
Sum input L
R10L
R7L
C7L
R13L
R14L
R11L
R12L
C9L
R4L
0V
Output L
C4L
C8L*
RS1
C5L
C10
C12
D1
R9
R8
IC1
C13
0V
V+
V–
C5R
D2
RS2
C11
C4R
C8R*
0V
Output
R12R
C9R
R4R
R14R
R11R
C7R
R7R
R13R
0V
Sum input R
R10R
R6R
Inverting input IC1b
R5R
C1R
R1R
C2R
C3R
0V
–input R**
+input R**
R3R
R2R
Non-inverting input IC1b
0V
Vbias
0V
Access these pads for linking signals to bias or 0V
Bias
R3R
R6R

**Ignore the error on the PCB's silkscreen, the Right input Molex +/– pin positions are as shown above.

*Note for C8L/R there is space for two devices so that capacitors can be in parallel, or an axial device.

Fig.30. Overlay for the dual op amp board. It's a shame to conceal its beautiful symmetry in a metal box, but hum pick-up is a nightmare with RIAA pre-amps because of the bass boost.


Sum input L
C4L
R7L
R14L
3.3kΩ
1%
C7L
C8L
330pF
5%
R10L
R11L
Bias L
R3L
C3L
22µF
16V
R5L
3.3kΩ
1%
–input pad L
0V
C1L
Input – L
Input + L
C2L
22µF
16V
V+
R4L
3.3kΩ
1%
IC1a
LM4562
2
3
1
+input pad L
R12L
47Ω
C9L
100µF
10V
Output L
R13L
100kΩ
R1L
100kΩ
R2L
100kΩ
R9L
Vb bias L
R6L
3.3kΩ
1%
C5L
330pF
5%
VbL
C13L
R8L
Link pads L
0V
Link
Used
Not used
Sum input R
C4R
R7R
R14R
3.3kΩ
1%
C7R
C8R
330pF
5%
Power input
0V
R10R
R11R
D2
BZY88C16
16V
RS2*
0.5W
0V
+ supply
– supply
Bias R
R3R
C3R
22µF
16V
R5R
3.3kΩ
1%
–input pad R
V+
C11
47µF
25V
0V
0V
C1R
Input – R
Input + R
6
5
8
7
4
IC1b
LM4562
C9R
100µF
10V
Output R
R12R
47Ω
C2R
22µF
16V
R4R
3.3kΩ
1%
+input pad R
C10
100nF
R13R
100kΩ
R1R
100kΩ
R2R
100kΩ
R6R
3.3kΩ
1%
RS1*
0.5W
V–
C5R
330pF
5%
D1
BZY88C16
16V
C12
47µF
25V
Link pads R
0V

*RS1/2: 2kΩ for ±43V supply, 22Ω for normal op amp supply (±15V)

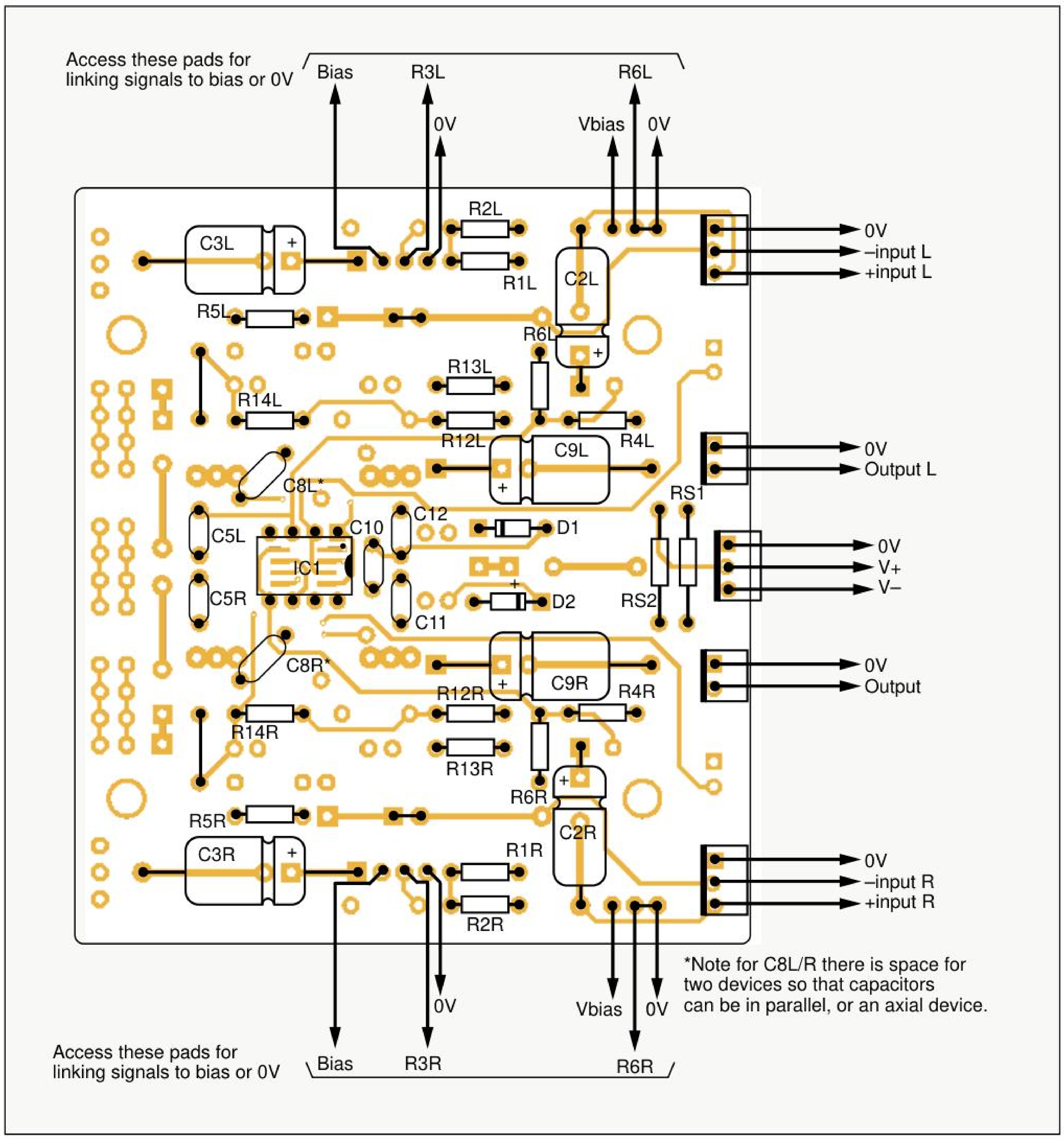
Fig.31. Dual-channel differential/ balanced input amplifier.

bridging impedance of 9.9kΩ across the input pins on the XLR. 10kΩ is the standard accepted minimum, so we are near enough. If the equipment driving the amplifier can accept a lower load impedance, such as 600Ω, reducing the resistance will reduce the Johnson noise. The overlay is shown in Fig.32 and the final assembled board in Fig.33. The photo in Fig.34 shows the board installed in an old Citronic SA 200 power amplifier, banishing its unbalanced jack inputs for a hum-free heaven. The power rails were ±43V and the Zener resistors (RS1 and RS2) were chosen to be 2kΩ 0.5W, dropping 27V. The current is split with the 16V Zener diodes (D1 and D2) passing 5mA, and the op amp 8mA. (Note that if you want just normal op amp supply voltages (±15V) then RS1/2 should both be 22Ω and the Zener diodes can be omitted).

Note that since the board mounting holes are connected to signal ground, an earth loop could develop with the mains safety earth if metal bolts are used. It's best to use plastic standoffs in this situation. A subtle point: adding the balanced input board made the amplifier have nasty turn-on/off thumps, somewhat negating its advantages. Of course, this problem only became apparent in the field, not on the test bench. I've found the 5534 series op amps to be especially bad in this regard. Replacing it with a LM4562 stopped the turn-off thump and gave slightly lower hiss. The switch-on thump was greatly reduced by putting a 470µF 35V electrolytic capacitor (C10) across the op amp's positive/negative power pins.

The vinyl countdown

For those of us who go round charity shops buying scratchy old sound effects records, it seemed sensible to make a



Access these pads for linking signals to bias or 0V

Access these pads for linking signals to bias or 0V

*Note for C8L/R there is space for two devices so that capacitors can be in parallel, or an axial device.

Fig.32. Overlay for dual balanced input board.

lower-cost stereo RIAA preamplifier using one board, useful for installing inside rescued cheap decks. It can be possible to derive the preamplifier power from the motor transformer using voltage-doubler networks. In the old days, when mains-powered synchronous motors were used, an overwind was sometimes placed on the coil, effectively making a transformer.

Going from two single NE5534s to a dual NE5532 incurs a small 1dB decrease in the signal to noise ratio (–77dB to –76dB referenced to 5mV input). The impedance of the feedback network was also doubled, as shown in Fig.24 (lower) in *Part 2*. This increases noise a little, but in the context of a needle ploughing a dust-filled groove, it is practically insignificant. However, the lower loading (442Ω at 20kHz) of the feedback network improves the overload performance on scratches. The circuit is shown in Fig.35, the overlay in Fig.36 and the assembled board in Fig.37.

If you want to use a single-rail power supply for this design, the half-rail bias network is deployed and the extra components are inserted. These comprise R9, R8 (both 22kΩ) and C13 22µF 25V. R6L and R6R must be connected to the bias pads via links.

Bidirectional caps

Note that the polarisation of electrolytic coupling capacitors does not matter with op amps on dual-rail supplies. It makes no real difference since aluminium electrolytic and solid-tantalum capacitors can tolerate a continuous reverse polarity of up to a few hundred millivolts. With the 5534 series of op amps, where high source impedances are presented to the input pins (as in the RIAA amplifier) input bias current flowing through the resistance always generates a small negative offset. These ICs have NPN input transistors run at a relatively high collector current, giving rise to significant input currents.

Components

The special value 1% RIAA equaliser components C7 (24.76nF), C8 (7.15nF), R5 (442Ω), R10 (127kΩ) and R11 (10.5kΩ) are available in a bargain pack from *PE PCB Service* or the author (see page 35 for contact details). Having built several of these boards and plotted their frequency responses on an Audio Precision analyser I was pleased to see all the plots matched looking like a single plot when overlaid. This shows the benefits of 1% tolerance devices and the near cancellation of the −200ppm/°C

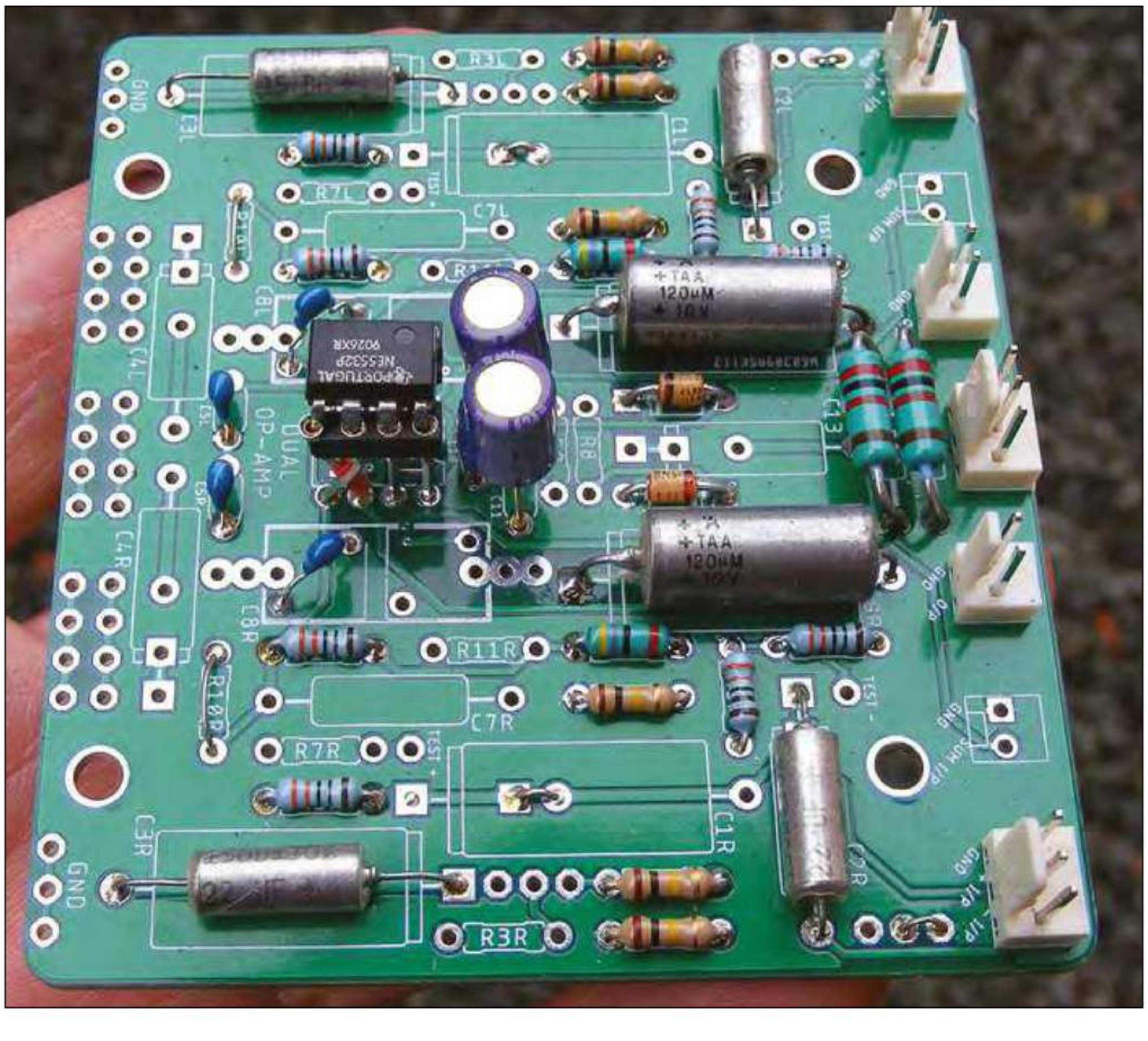


Fig.33. A view of the stuffed dual balanced input board. For the eagle-eyed among you, note that there was a small error on this prototype board – the op amp's pin 5/6 connections were reversed. This has been corrected for production boards. (They will also have a smart red silk screen!)

negative temperature coefficient of polystyrene capacitors with the +100ppm/°C positive coefficient of metal-film resistors.

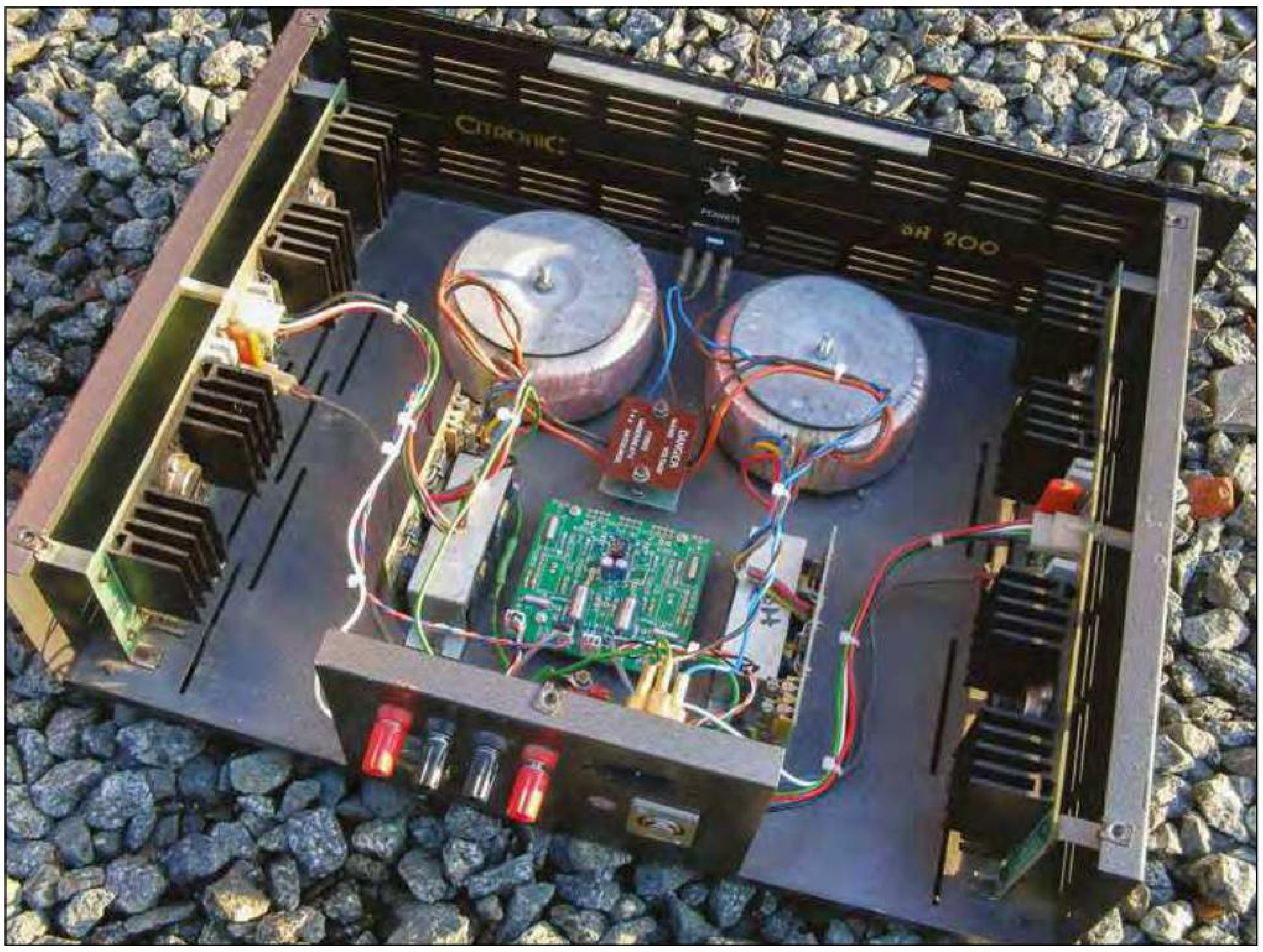


Fig.34. Another view of the assembled balancing board installed in a power-amplifier.

Distorted view

I thought it would be interesting to measure the distortion of the RIAA amplifier with regard to the high gain and complex filtering. Interestingly, the only way I could get meaningful results was to precede the RIAA amplifier with a passive inverse RIAA filter – shown in Fig.38 – to get an overall (theoretical) flat frequency response. This attenuation followed by gain, gives rather high noise and hum levels which are added to the distortion residual. The end result was a total harmonic distortion and noise (THD+N) figure of 0.02%, as shown in Fig.39. This is ten-times higher than a normal non-inverting 5532 amplifier with moderate gain. I thought this was bad, but other amplifiers I measured were much worse. Again, in the context of vinyl playback distortion, typically in the order of a few percent, it is little to worry about. However, distortion plots do reveal much about amplifier behaviour during design, even if its effect may never be heard. A strange surprise was that the THD+N was lower with the single-rail version. I suspect additional power supply noise was to blame.

A useful device

These general-purpose op amp boards were designed with experimentation in mind and of course that's what happened while messing about with the RIAA board. I was thinking about the power supply for a single-rail RIAA preamplifier, and it suddenly struck me: why not make it phantom powered? This would be very useful because most mixing desks and USB audio interfaces have microphone inputs (with phantom power) not RIAA inputs for record decks. A quick conflab with Mike Grindle revealed he was wondering how to connect a record deck to his mixer for a gig and my son had a similar problem with a Focusrite computer interface. The classic and expensive way of phantom powering a circuit is to use output transformers and harness the power from

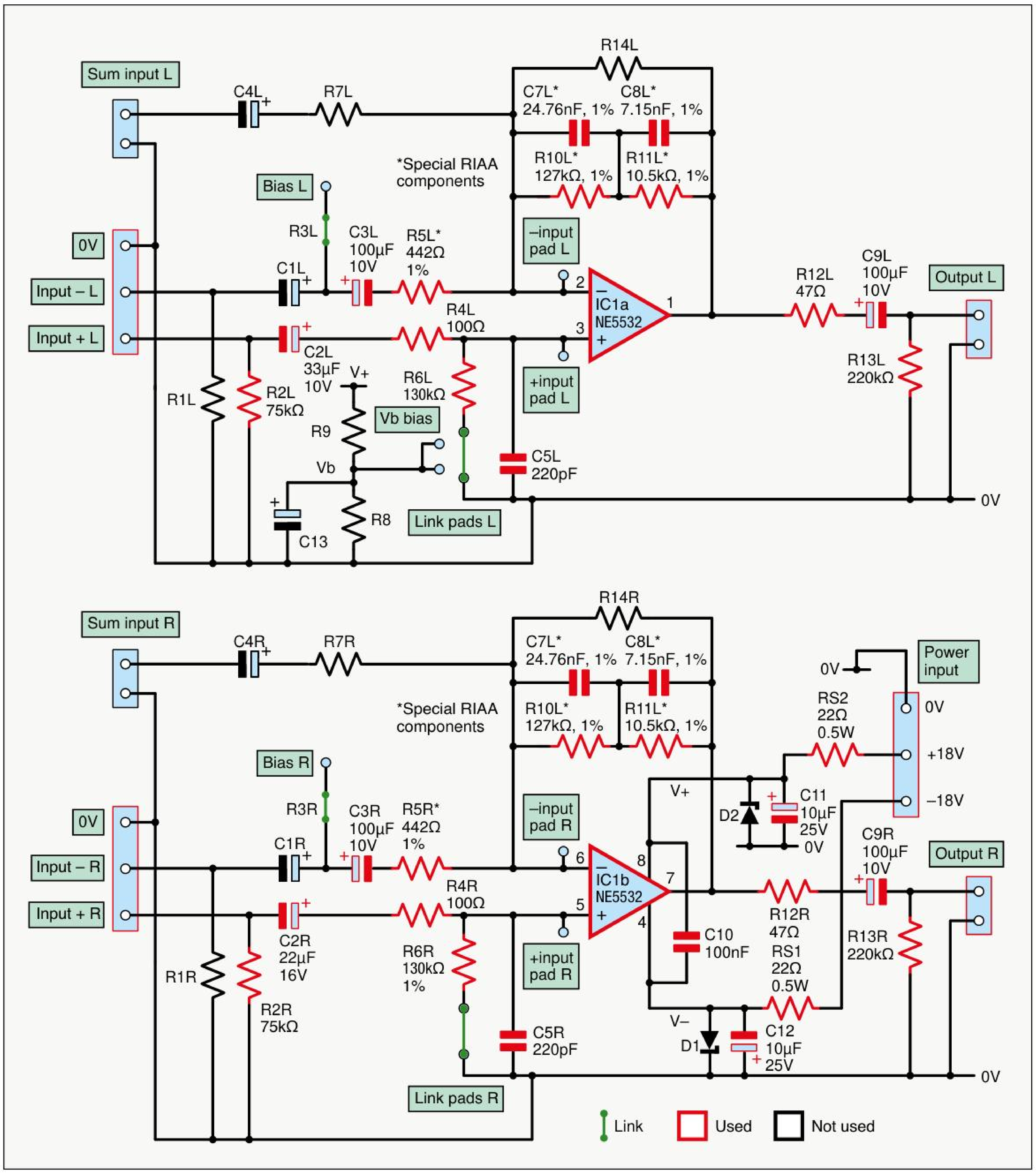

R14L
Sum input L
C4L
R7L
C7L*
24.76nF, 1%
C8L*
7.15nF, 1%
*Special RIAA components
R10L*
127kΩ, 1%
R11L*
10.5kΩ, 1%
Bias L
R3L
C3L
100µF
10V
R5L*
442Ω
1%
–input pad L
0V
C1L
Input – L
Input + L
R4L
100Ω
2
3
1
IC1a
NE5532
R12L
47Ω
C9L
100µF
10V
Output L
C2L
33µF
10V
V+
R6L
130kΩ
+input pad L
R13L
220kΩ
R1L
R2L
75kΩ
R9
Vb bias
Vb
C5L
220pF
0V
C13
R8
Link pads L
R14R
Sum input R
C4R
R7R
C7L*
24.76nF, 1%
C8L*
7.15nF, 1%
0V
Power input
*Special RIAA components
R10L*
127kΩ, 1%
R11L*
10.5kΩ, 1%
RS2
22Ω
0.5W
0V
+18V
Bias R
V+
D2
C11
10µF
25V
0V
–18V
R3R
C3R
100µF
10V
R5R*
442Ω
1%
–input pad R
C9R
100µF
10V
Output R
0V
C1R
Input – R
Input + R
6
8
7
5
4
IC1b
NE5532
R4R
100Ω
R12R
47Ω
RS1
22Ω
0.5W
R13R
220kΩ
C2R
22µF
16V
R6R
130kΩ
1%
+input pad R
C10
100nF
R1R
R2R
75kΩ
V–
D1
C5R
220pF
C12
10µF
25V
0V
Link pads R
Link
Used
Not used

Fig.35. Stereo RIAA pre-amplifier circuit. The special RIAA equalisation components marked * are available as a kit from the PE PCB Service.

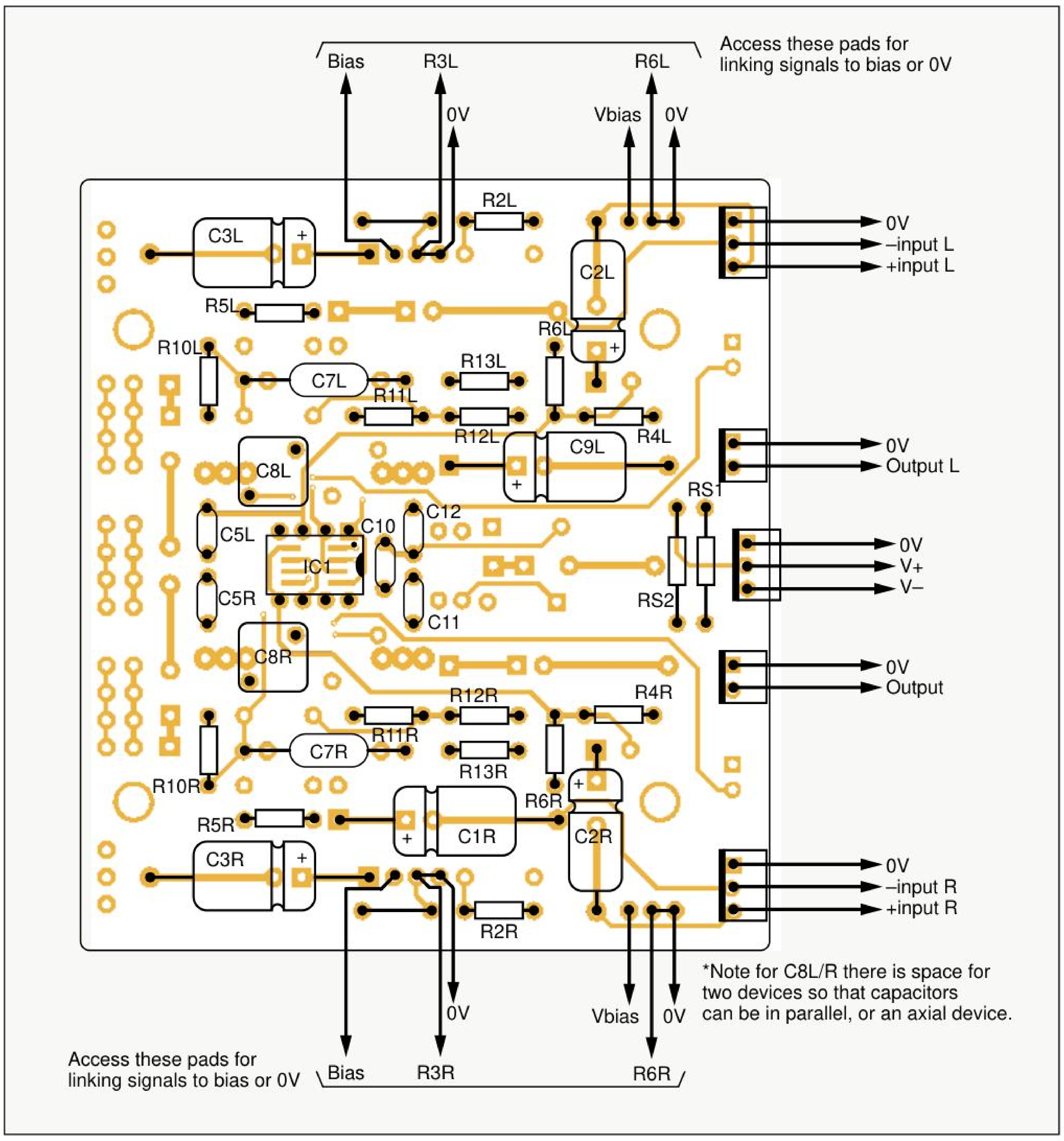

Access these pads for linking signals to bias or 0V
Bias
R3L
R6L
0V
Vbias
0V
R2L
C3L
+
C2L
0V
–input L
+input L
R5L
R6L
+
R10L
R13L
C7L
R11L
R12L
C9L
R4L
+
0V
Output L
C8L
RS1
C12
C10
C5L
0V
V+
V–
IC1
C5R
RS2
C11
C8R
0V
Output
R12R
R4R
R11R
C7R
R13R
R10R
+
R6R
R5R
+
C1R
C2R
C3R
+
0V
–input R
+input R
R2R
*Note for C8L/R there is space for two devices so that capacitors can be in parallel, or an axial device.
0V
Vbias
0V
Access these pads for linking signals to bias or 0V
Bias
R3R
R6R

Fig.36. Overlay for the stereo RIAA amplifier.

a centre tap, as shown in Fig.40. The physical 'lash-up' is shown in Fig.41.

A few measurements of the current capability of some representative phantom-powered input XLRs showed a typical maximum current delivery of 6.6mA. This concurs with the standard dual 6.8kΩ feed resistors used. Most commercial units tested gave less than the official +48V. A £29 Behringer mixer gave +44V and the Focusrite gave +46.5V. However, it was clear that it was possible to power a 5532 op amp, that typically needs a 30V single rail drawing 8mA. The setup was tested and worked perfectly. However, the transformers were expensive (at least £20 a pair) and I was worried about the stress on the single op amp chip, already doing 50dB gain at 20Hz, along with turntable rumble, possibly saturating the transformer cores. My usual approach is to prove a concept works with no-compromise expensive parts – and then find a way of doing it for less. The transformers' unique advantage, a floating output, was not realisable here anyway, because of the earth return required for the phantom power.

Quasi-balancing

Since the output of the RIAA amplifier is around 150 to 600mV$_{pk-pk}$ with a typical moving magnet cartridge, a truly balanced output is not necessary for low noise. It is perfectly satisfactory to drive just one leg of the balanced line. The other leg is held at the same impedance to ground to obtain common-mode interference rejection of the balanced input. Of course, both lines can be used to provide phantom power. This is blocked off by capacitors and steered to the op amps' power rail via resistors. Unlike the centre-tapped transformer supply where cancellation occurs, there is audio riding on top of the +48V DC, so a big supply decoupling capacitor (C11) is necessary. The circuit is shown in Fig.42. Connecting the 820Ω phantom feed resistors must be done partly off-board, as shown in Fig.43a.

Lighting-up time

It's a good idea to put in a low-current LED to show phantom power is present (there could be one for each XLR). I use Kingbright L-7104SEC orange LEDs because they are bright enough with 1mA. They are 'costly' (for LEDs) at 25p from Rapid (part No. 72-8972),

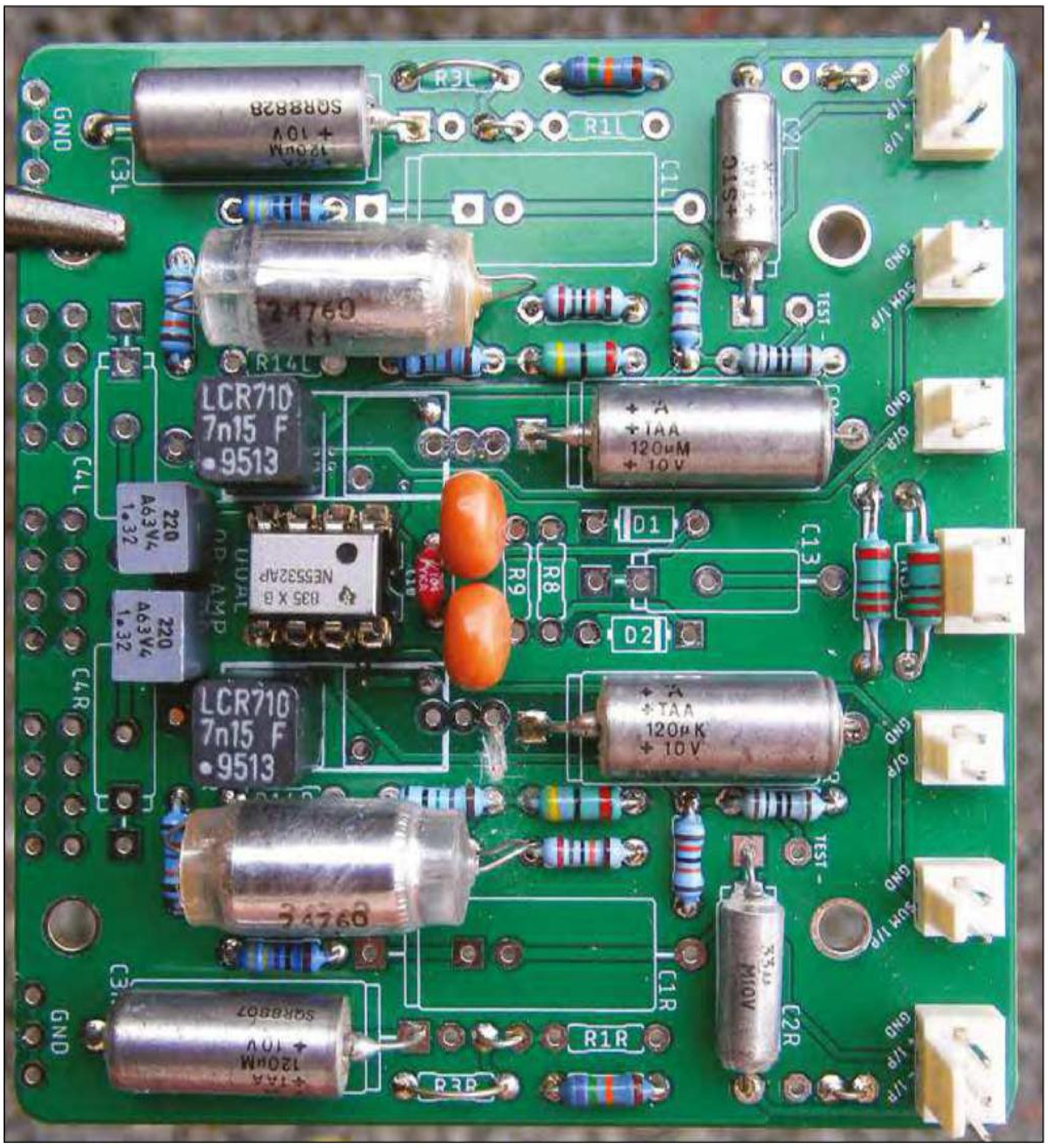
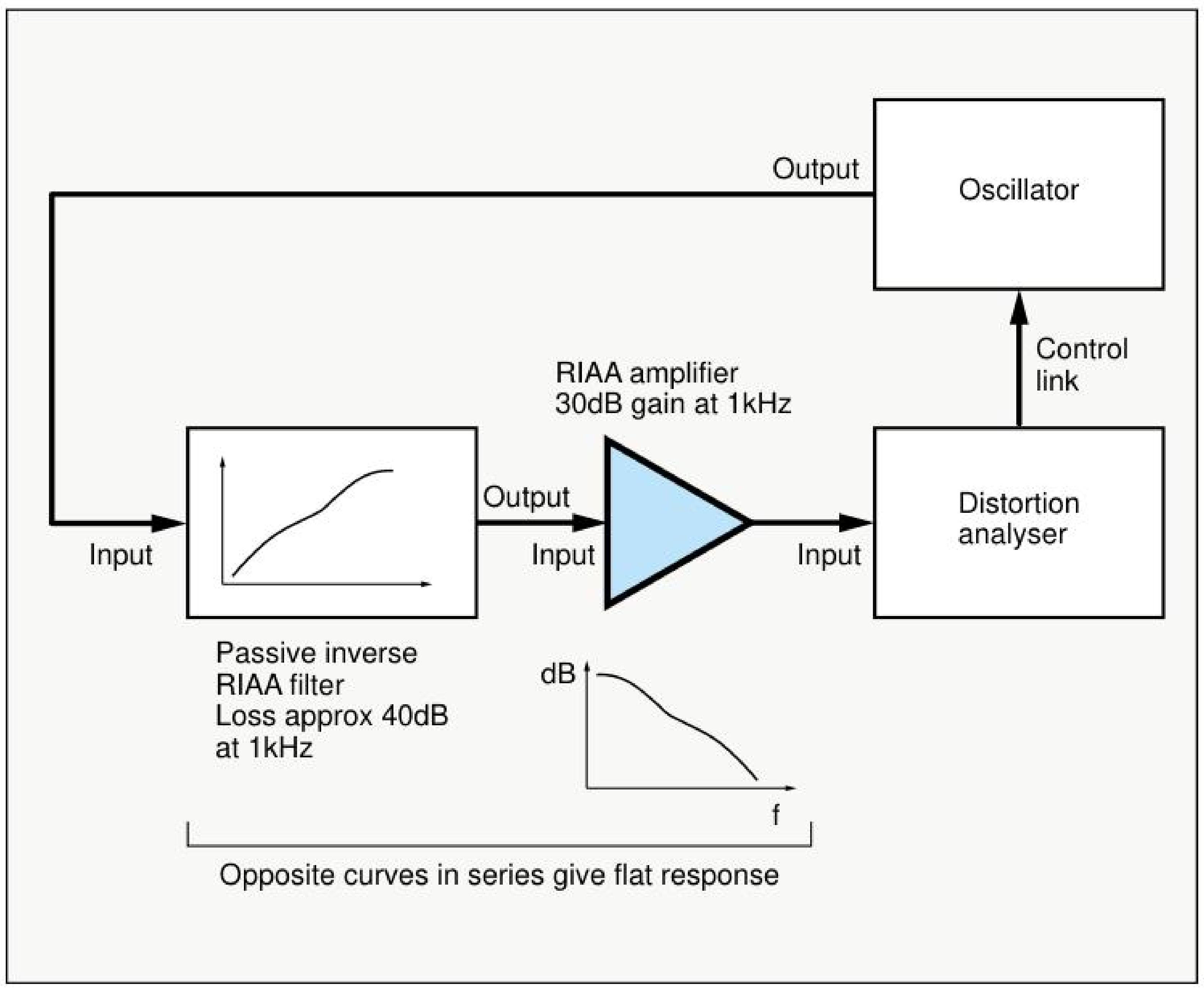

GND
C3L
R3L
R1L
C1L
C2L
R14L
LCR710
7n15 F
9513
C4L
NE5532AP
D1
D2
R9
R8
C13
C4R
LCR710
7n15 F
9513
C3R
GND
C1R
C2R
R1R
R3R
TEST
GND

Fig.37. Assembled stereo RIAA PCB.


Output
Oscillator
Control link
RIAA amplifier
30dB gain at 1kHz
Input
Output
Input
Input
Distortion analyser
Passive inverse
RIAA filter
Loss approx 40dB
at 1kHz
dB
f
Opposite curves in series give flat response

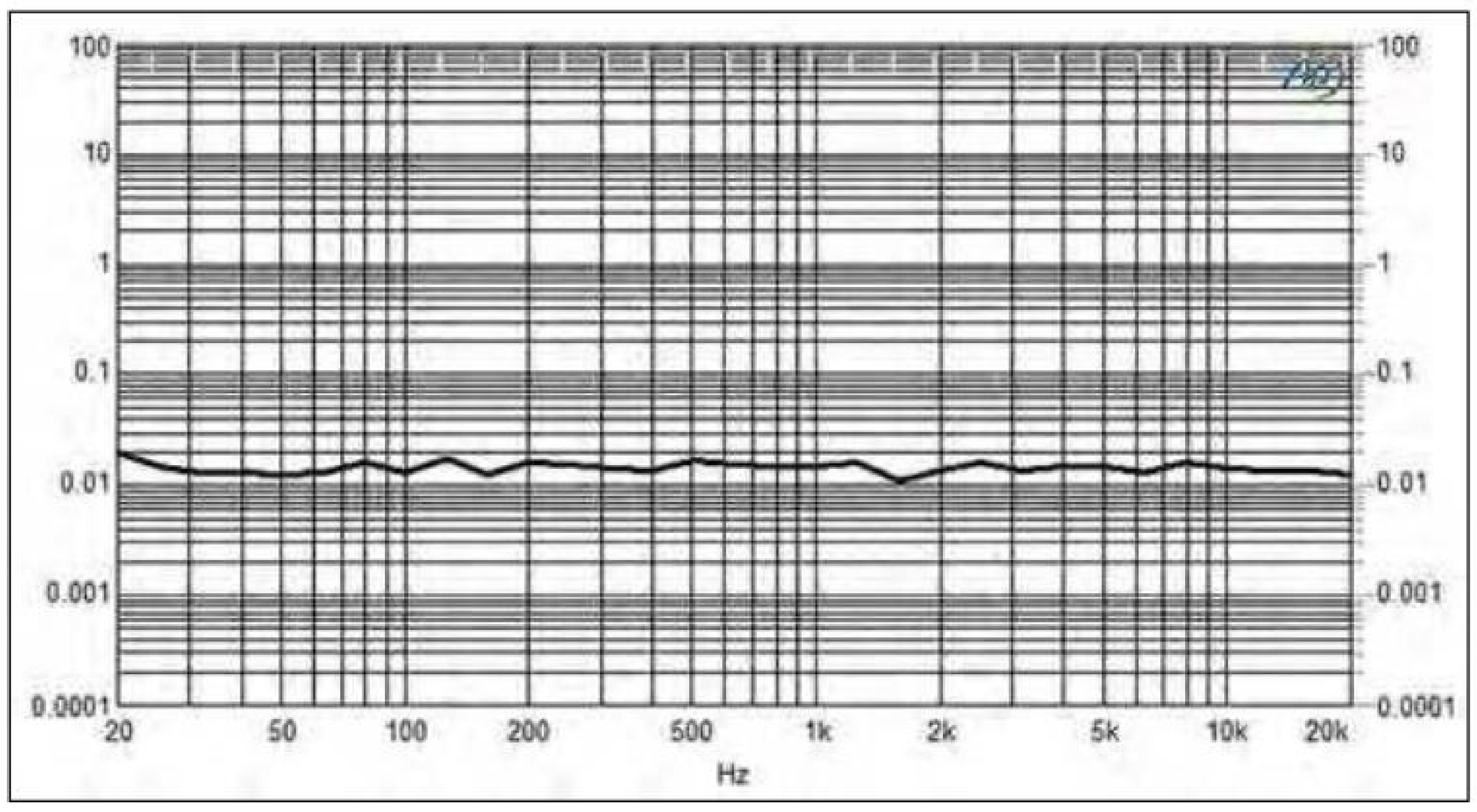


Fig.38. (left) Plotting the distortion of RIAA amplifiers is tricky. In this set-up, the overall frequency response is rendered flat by inserting an inverse RIAA filter on the input.

Fig.39. (above) Distortion plot for RIAA amplifier using an NE5532. Most of the distortion was noise due to the massive attenuation (-40dB) from the inverse filter.

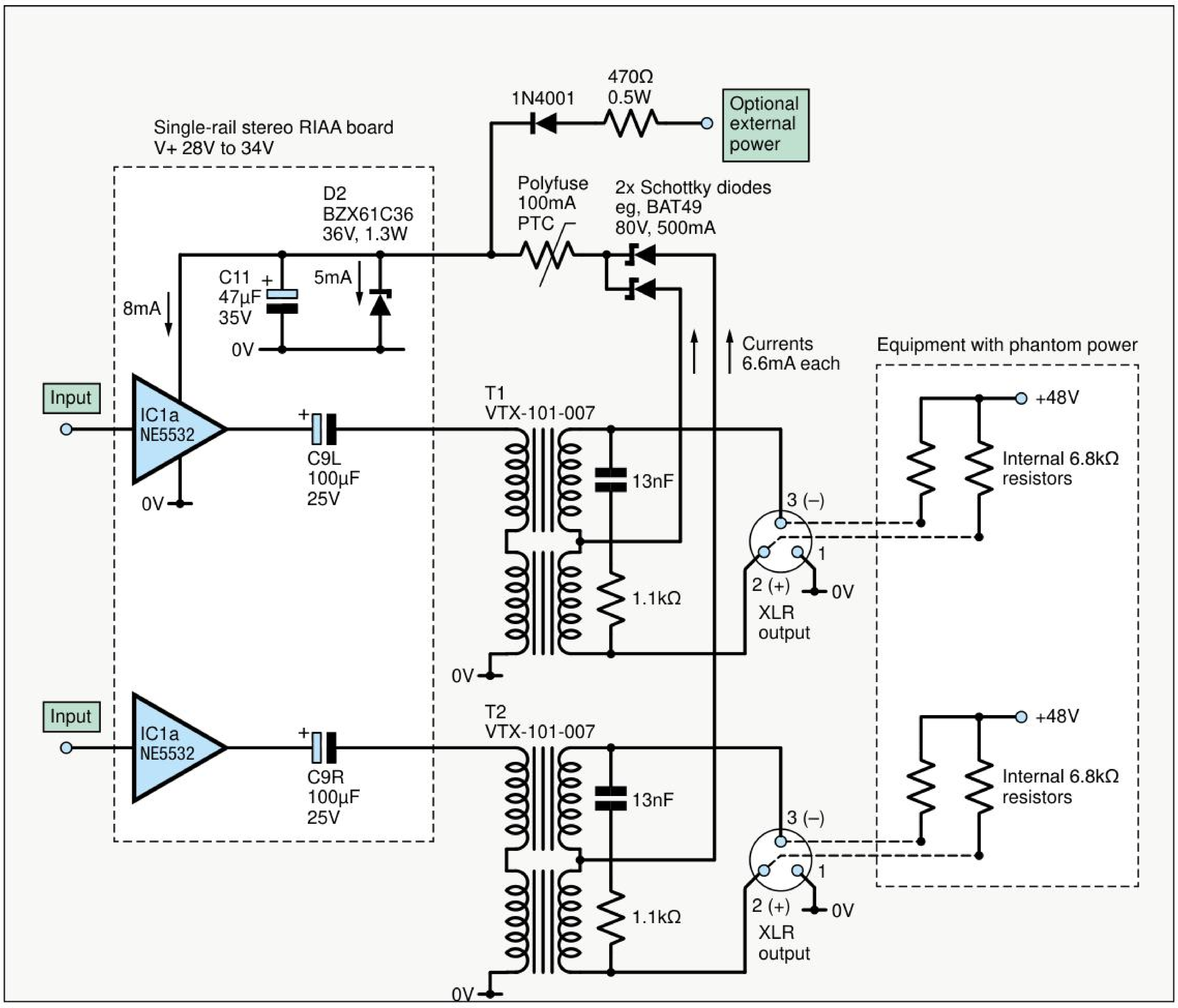

Single-rail stereo RIAA board
V+ 28V to 34V
1N4001
470Ω
0.5W
Optional external power
D2
BZX61C36
36V, 1.3W
Polyfuse
100mA
PTC
2x Schottky diodes
eg, BAT49
80V, 500mA
C11
47µF
35V
5mA
8mA
0V
Currents
6.6mA each
Equipment with phantom power
Input
IC1a
NE5532
C9L
100µF
25V
0V
T1
VTX-101-007
13nF
1.1kΩ
+48V
Internal 6.8kΩ resistors
3 (–)
1
2 (+)
0V
XLR output
0V
Input
IC1a
NE5532
C9R
100µF
25V
T2
VTX-101-007
13nF
1.1kΩ
+48V
Internal 6.8kΩ resistors
3 (–)
1
2 (+)
0V
XLR output
0V

Fig.40. Feeding a circuit from phantom power using output transformers.

but worth it. Every milliamp counts in this application. To power the LED, I used four 150kΩ resistors connected to each XLR live pins, as shown in Fig.43b. The maximum voltage available on a 5532 op amp with this phantom power circuit is 27V. However, this increases to 32V using an LM833 (an early National Semiconductors audio op amp) which works just as well in this application.

Adapting the board

Universal boards can often end up rather messy – as shown in the overlay in Fig.44 – illustrating the adaptation of a single-rail stereo RIAA board. Note the spare input on the balanced input connector is used to feed the 'fake' balanced output pin to its grounded capacitor (C1).

All boxed up

Since we now have no big transformers to worry about, the PCB, two phono connectors and two male XLR connectors can all be fitted in a neat Hammond diecast box, as shown in Fig.45. The final unit of symmetrical design, shown in Fig.46, can be placed alongside the turntable, where its low impedance output will drive very long cables. It is effectively a phantom-powered RIAA direct-inject (DI) box.

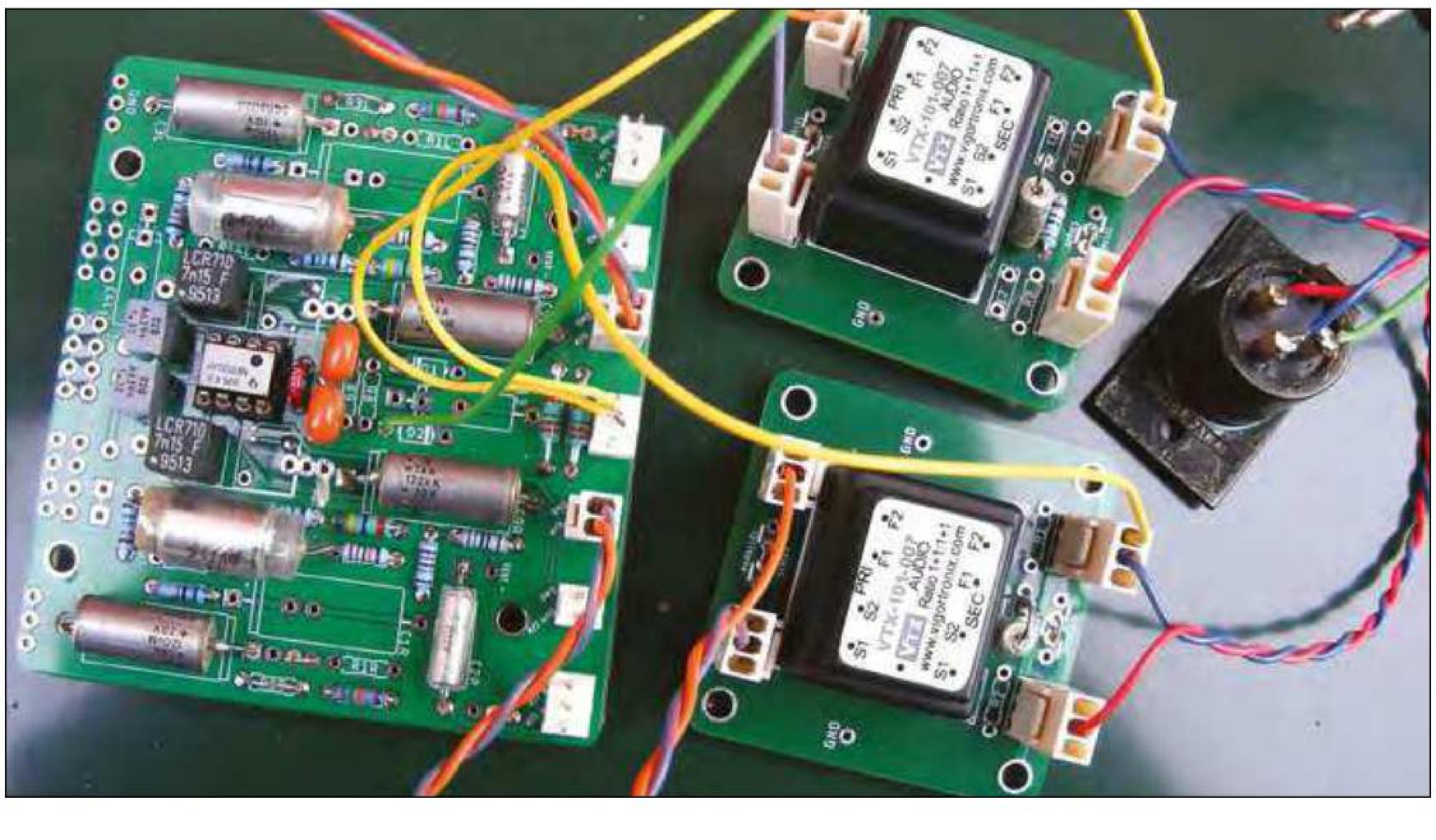


Fig.41. The dual op amp board can be phantom-powered using a pair of Vigotronix transformers wired centre-tapped to obtain a 48V output (yellow wire), as shown here using the *PE* transformer mounting boards.

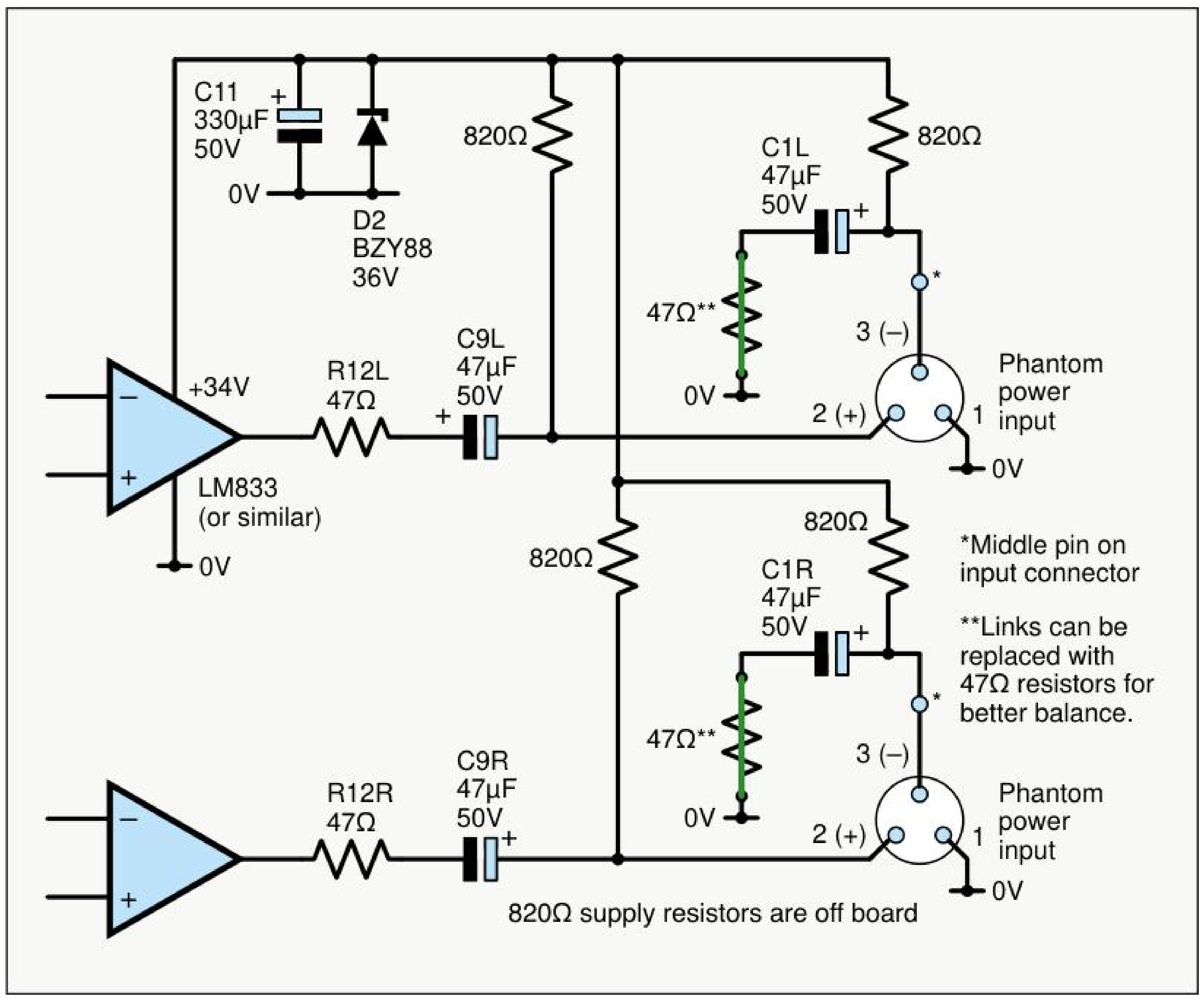

C11
330µF
50V
+
0V
D2
BZY88
36V
820Ω
820Ω
C1L
47µF
50V
+
47Ω**
*
3 (–)
0V
2 (+)
1
Phantom
power
input
0V
+34V
R12L
47Ω
C9L
47µF
50V
+
LM833
(or similar)
0V
820Ω
820Ω
C1R
47µF
50V
+
*Middle pin on
input connector
**Links can be
replaced with
47Ω resistors for
better balance.
47Ω**
*
3 (–)
0V
2 (+)
1
Phantom
power
input
0V
R12R
47Ω
C9R
47µF
50V
+
820Ω supply resistors are off board

Fig.42. Circuit for phantom powered, quasi-balanced outputs. This trick is often used in 'transformerless' microphones, such as the Neumann TLM170.

Mis-cued tracks

An eagle-eyed reader has noticed that the links near R6 on the single channel RIAA board in Fig.23 *Part 2* have to be dropped down by one hole. The links are shown correctly in the photo of Fig.24 (upper) *Part 2*.

PCB / RIAA parts

The Dual Op amp PCB (AO1-APR23) and the stereo RIAA set of precision capacitors and resistors (AO2-APR23) are available from the *PE PCB SERVICE*.

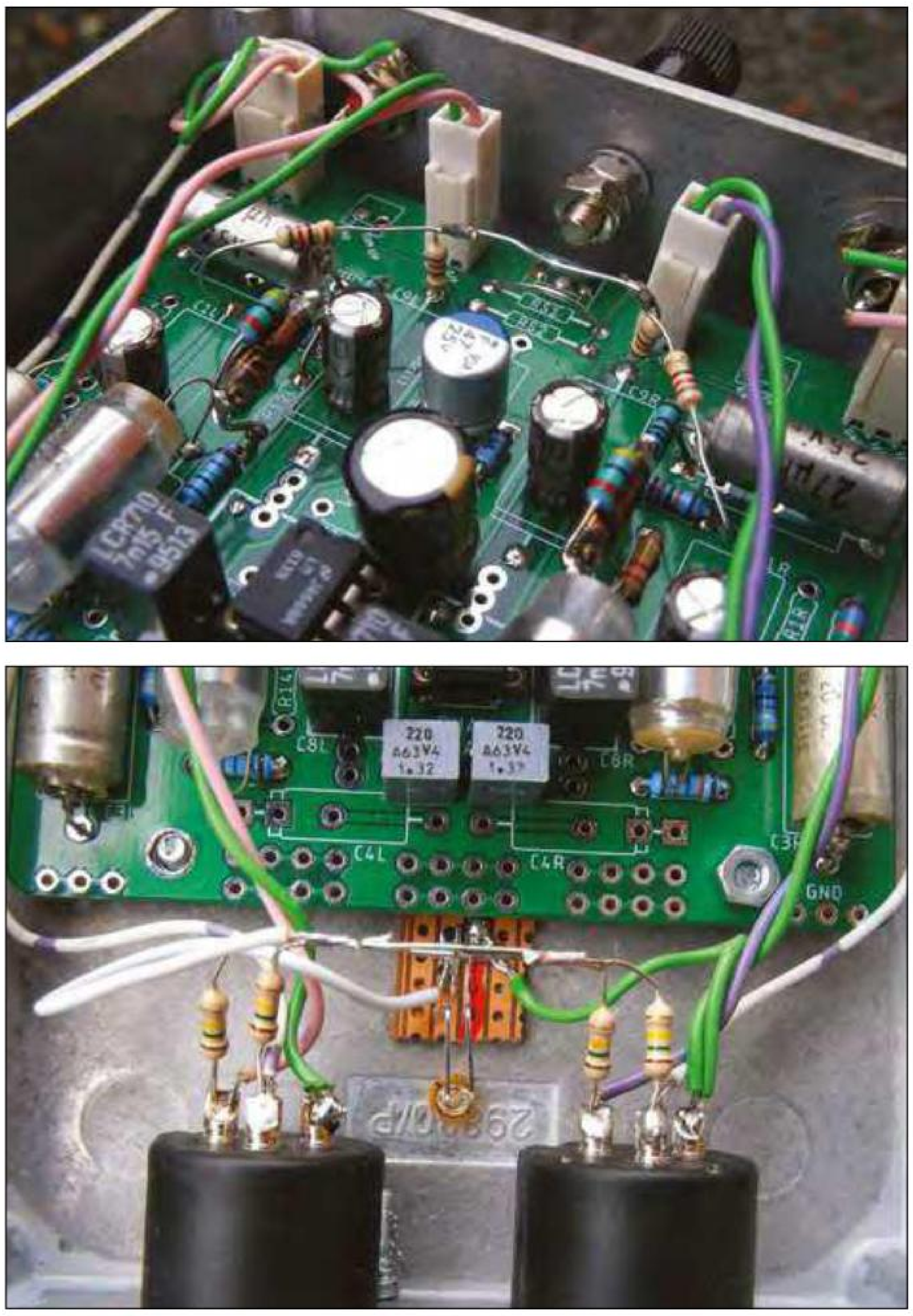
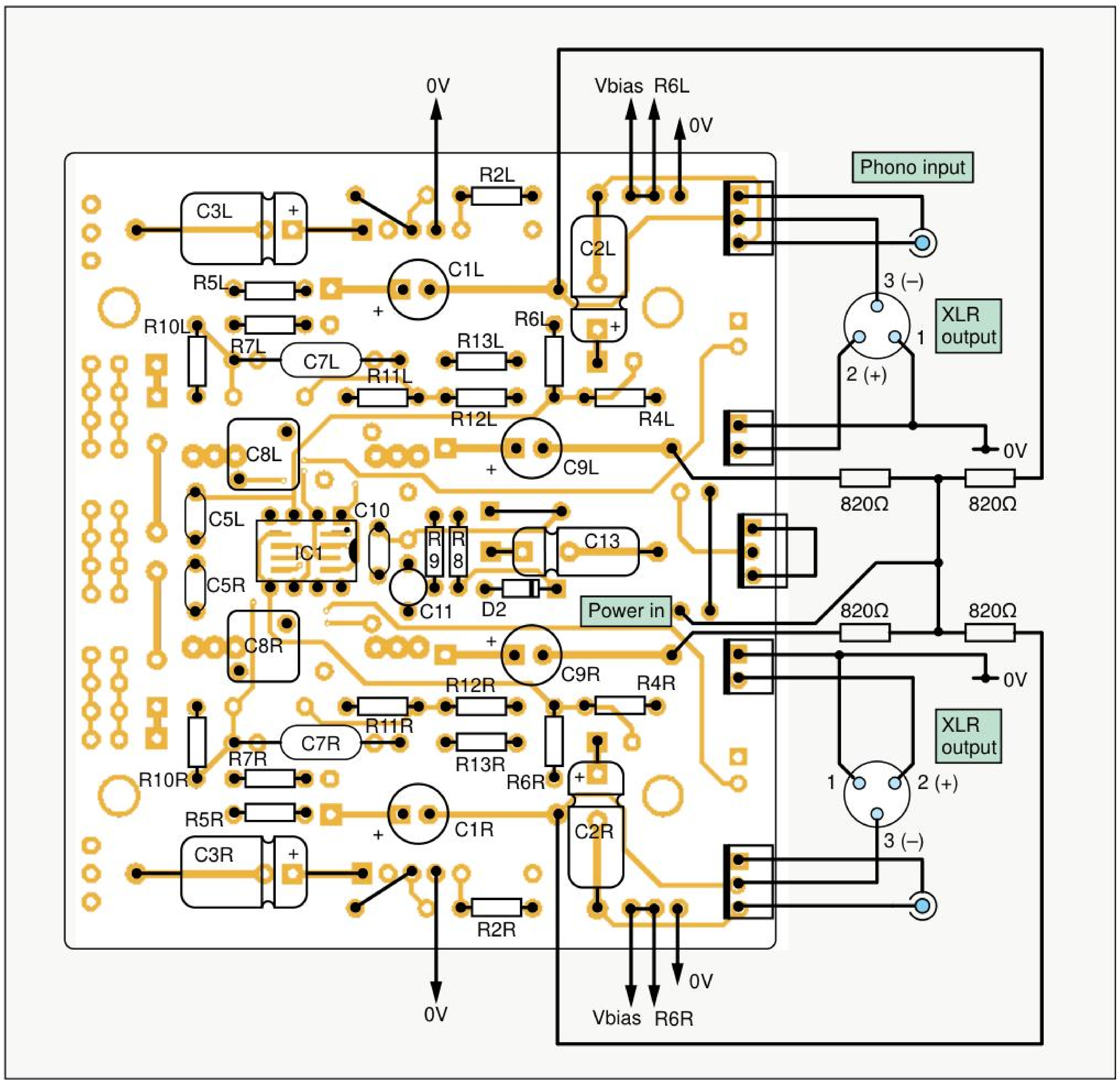


Fig.43. a) (top) The phantom power is collected together via four 820Ω resistors and fed into the board; b) (below) using four 150kΩ resistors to powering an LED to show phantom power is on.

Fig.44. (below) Overlay for the phantom powering components on the PCB.


0V
Vbias
R6L
0V
Phono input
R2L
C3L
C1L
C2L
R5L
3 (–)
R10L
R6L
XLR
output
1
R7L
C7L
R13L
R11L
2 (+)
R12L
R4L
C8L
C9L
0V
820Ω
820Ω
C5L
C10
R9
R8
C13
IC1
C5R
C11
D2
Power in
820Ω
820Ω
C8R
C9R
R4R
0V
R12R
R11R
C7R
XLR
output
R7R
R13R
R10R
R6R
1
2 (+)
R5R
C1R
C2R
C3R
3 (–)
R2R
0V
0V
Vbias
R6R

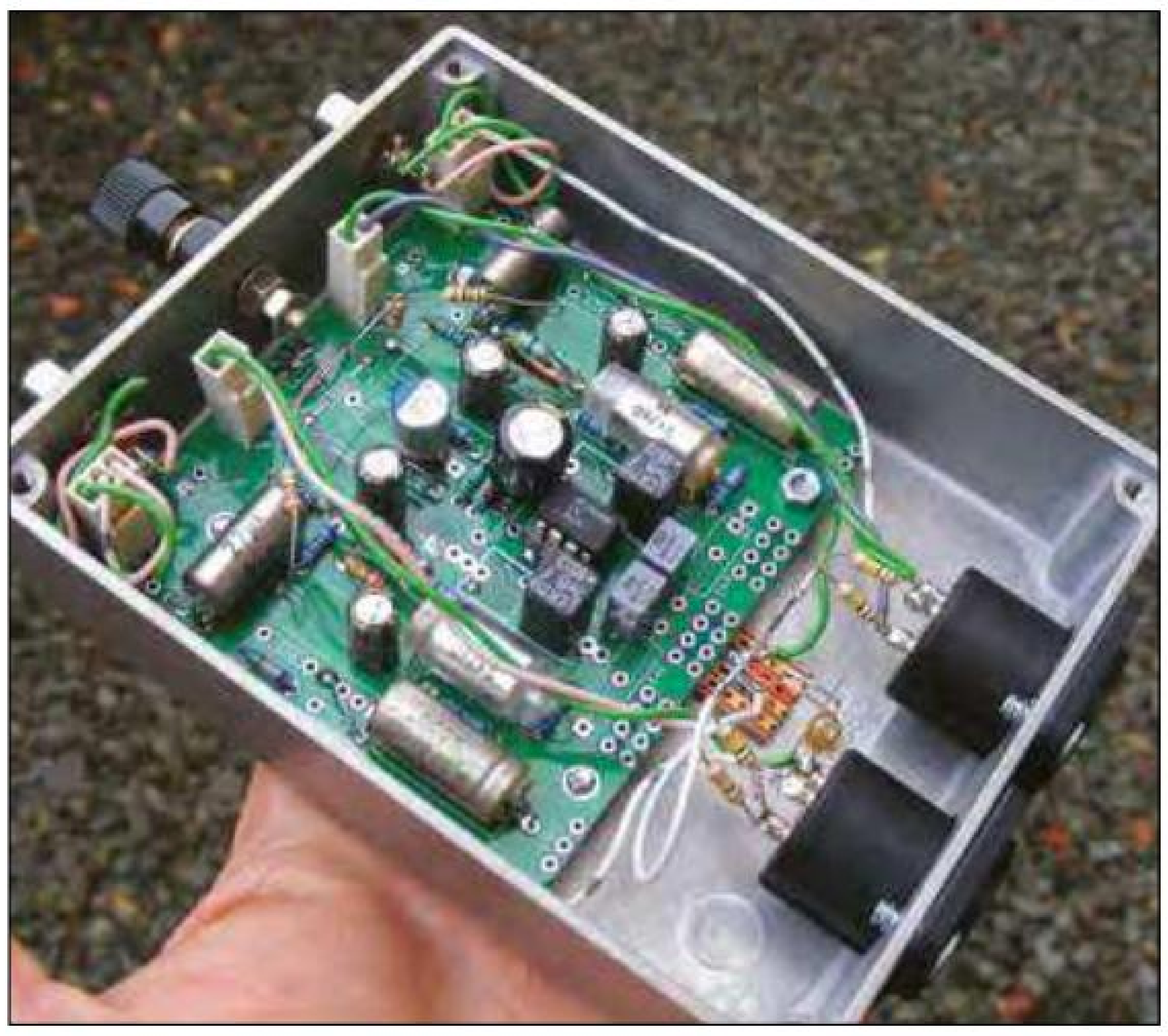


Fig.45. The assembled phantom-powered RIAA preamplifier interior.

Fig.46. Finished phantom-powered RIAA pre-amp.

Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 4

Hello there – how's your day going? I'm having an awesome time (thanks for asking). One of the great things about writing for *PE* is receiving emails from readers around the world saying how wonderful I am. Actually, if the truth be told, these messages are usually focused on my columns, but I'm reading between the lines, as it were.

For example, I just heard from retired computer studies teacher Tom Boyd, who describes himself as 'a computer addict since when programming was done with paper tape.' As Tom noted, 'The internet is all well and good, but a properly produced product like *Practical Electronics* is so much better!' Tom went on to say, 'I am a long-time Arduino evangelist and I love what you're doing with your *Arduino Bootcamp* articles to get more people started.'

Of particular interest to us here, Tom introduced me to his website, which contains a cornucopia of Arduino-related goodies, projects, and 'How To' guides: **https://bit.ly/3WFTQp4**

Ooh! Shiny!

Let's kickoff with a little pizazz. After all, who deserves it more than us? Assuming you've still got your 7-segment display wired up the way we left things in our previous column (*PE*, March 2023), then download file **CB-Apr23-06.txt** – all the files mentioned in this column are available from the April 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

Now, launch your Arduino integrated development environment (IDE). Use the File > New Sketch command to create a new program, then use the File > Save As command to save this file with a name of your own choosing (the name *Hello-Count* would work if you happen to find yourself filename challenged). Next, we want to delete the existing contents of this file and replace it with the contents of our **CB-Apr23-06.txt** file. If any of this is new to you, all you need do is open the **CB-Apr23-06.txt** file with your text editor and use the editor's Edit > Select All command followed by the Edit > Copy command to select and copy the contents of the file to your computer's clipboard. Now, place your cursor in the Arduino IDE window and use its Edit > Select All command followed by its Edit > Paste command to select its existing contents and overwrite them by pasting the contents of the clipboard into the IDE.

Before you do anything else, use the IDE's File > Save command to save your updated program contents. Now, make sure your Arduino Uno is connected to your host computer via its USB cable, then use the IDE's Sketch > Upload command to load the program into your Arduino and run it. You should see the 7-segment display present a cheery 'HELLO' greeting, after which it will start to count from 0 to 9 repeatedly. The rest of this column will walk us through the various elements we've brought together to make this program perform its magic.

We all count!

As Mickey Mouse famously said, 'Arithmetic is being able to count up to twenty without taking off your shoes,' and who amongst our number (no pun intended) would argue with logic like that?

Speaking of numbers, since ancient peoples counted using their fingers, and given that we are equipped with ten fingers (including thumbs), the number system with which we are most familiar is decimal (a.k.a. 'denary'). As decimal has ten digits (0, 1, 2, 3, 4, 5, 6, 7, 8, 9), it's said to be base-10 or radix-10.

Decimal is a place-value number system, which means the value of a digit depends on the digit itself and its location (place) within the number. If we visualise the digits as being presented in columns, then each column has a 'weight' associated with it, where these weights are powers of ten. Starting with the right-hand digit, which is known as the least-significant digit (LSD), these weights are $10^0 = 1$, $10^1 = 10$, $10^2 = 10 \times 10 = 100$, $10^3 = 10 \times 10 \times 10 = 1000$, and so on.

Each digit forming a decimal number is multiplied by its column's weight and the results are summed to give the total value of that number. For example, we understand 6174, which is known as Kaprekar's constant after the Indian mathematician Dattatreya Kaprekar, to be: (6 x 1000) + (1 x 100) + (7 x 10) + (4 x 1).

Suppose we wish to count in decimal. Starting with 0 in the first column, we keep incrementing (adding 1 to) our first column until we reach 9, at which point we've exhausted all of our digits. Thus, the next time we add 1, we reset the first column to 0 and increment the next column to 1, thereby resulting in 10. Similarly, when we reach 99, we set the first two columns to 0 and increment the third column, resulting in 100, and so it goes… for ever.

I'm reasonably sure you're saying to yourself, 'Good grief! All of this is painfully obvious,' but hold onto your hat because we are setting the scene for the ~~horrors~~ delights that are to come.

Take a number!

As we discussed in *Part 3* (*PE*, March 2023), we can use transistors to create simple logical building blocks that can detect the difference between two voltage values and present the results of their operations in terms of the same two voltages. These building blocks can be connected to create larger functions, which can themselves be connected to realise sophisticated systems like computers – see my column, *Arduino 0s and 1s, LOW and HIGH, False and True and Other Stuff* at: **https://bit.ly/3DeMQsl**

Rather than think in terms of voltages, we prefer to think in terms of 0s and 1s. This leads us to the binary number system, which is said to be base-2 or radix-2. A binary digit, which is known as a 'bit,' can assume only two values: 0 or 1.

Like decimal, binary is a place value system. In this case, however, the column weights are powers of two. Starting with the right-hand bit, which is known as the least-significant bit (LSB), these weights are: $2^0 = 1$, $2^1 = 2$, $2^2 = 2 \times 2 = 4$, $2^3 = 2 \times 2 \times 2 = 8$, and so on.

As before, each bit forming a binary number is multiplied by its column's weight and the results are summed to give the total value of that number. For example, we understand 1100 in binary to be: $(1 \times 8) + (1 \times 4) + (0 \times 2) + (0 \times 1) = 12$ in decimal.

Counting in binary is easy-peasy lemon squeezy (Fig.1). As with decimal, we start with 0 in the LSB. Actually, we start with

Binary $2^3 2^2 2^1 2^0$	Decimal
0 0 0 0	0
0 0 0 1	1
0 0 1 0	2
0 0 1 1	3
0 1 0 0	4
0 1 0 1	5
0 1 1 0	6
0 1 1 1	7
1 0 0 0	8
1 0 0 1	9
1 0 1 0	10
1 0 1 1	11
1 1 0 0	12
1 1 0 1	13
1 1 1 0	14
1 1 1 1	15

Fig.1. Binary vs decimal.

0s in all of the bits. This is as good a time as ever to note that we usually write binary numbers with leading 0s, which serves to indicate the size of the bus, field, or memory location being used to represent and/or store the value. For example, 0101 tells us we are working with a *4*-bit binary number whose current value is 5 in decimal. By comparison, 00000101 indicates we are working with an *8*-bit binary number whose current value is, once again, 5 in decimal.

So, when counting with a 4-bit binary number, we start with 0000 (0 in decimal). In this case, as soon as we've added 1 to the LSB to give 0001 (1 in decimal), we've already exhausted all of our digits. Thus, the next time we wish add 1, we reset the first column to 0 and increment the next column to 1, thereby resulting in 10 (2 in decimal). Similarly, when we reach 11 (3 in decimal), we set the first two columns to 0 and increment the third column, resulting in 100 (4 in decimal), and so it goes.

Fancy a nybble?

As we previously noted, a binary digit, which is called a bit, can adopt only two values: 0 and 1. It doesn't take long to realise that there's a limit to what we can accomplish with a single bit. The solution is to gather groups of bits together, and to then use these groups to represent things like numbers or characters.

Some grouping sizes are more common than others. One very common grouping is eight bits, which is known as a 'byte'. This term, which is a deliberate respelling of 'bite' to avoid accidental mutation to 'bit', was coined by the German-American computer scientist Werner Buchholz in 1956.

Another common grouping is four bits, which is known as a 'nybble' (or 'nybl' or 'nibble'). The fact that two nybbles make a byte is considered to be the height of humour by computer scientists, which goes some way to explain why they don't get invited to parties.

BCD 8421	BCD 2421	Excess-3	Decimal
0000	0000	0011	0
0001	0001	0100	1
0010	0010	0101	2
0011	0011	0110	3
0100	0100	0111	4
0101	1011	1000	5
0110	1100	1001	6
0111	1101	1010	7
1000	1110	1011	8
1001	1111	1100	9

Fig.2. Three flavors of binary-coded decimal (BCD).

Binary-coded decimal (BCD)

Unfortunately, we now have something of a dichotomy when it comes to number systems. On the one hand (no pun intended), we have people who prefer to work in decimal (base-10). On the other grasping appendage, we have computers, which prefer to perform their magic using binary (base-2).

One solution is to employ a class of binary encodings of decimal numbers that we collectively call binary-coded decimal (BCD). Since four bits can represent $2^4 = 2 \times 2 \times 2 \times 2 = 16$ different combinations of 0s and 1s, it takes only four bits to encode (map) our ten decimal values, leaving six combinations unused. In fact, there are a variety of mapping possibilities, three of which (BCD 8421, BCD 2421, and Excess-3) are illustrated in Fig.2.

The form of BCD with which most people are familiar is formally known as BCD 8421, where the numbers refer to the weights of the four columns. In fact, this form is so common that if you say BCD, everyone will assume you are talking about BCD 8421. As we see, these are the same weights as for the natural binary number scheme we presented in Fig.1 (ie, 2^3, 2^2, 2^1 and 2^0, which equate to 8, 4, 2, and 1, respectively). We use the term 'natural' in this context because it follows the general counting method employed in decimal and other place-value numbering systems. For this reason, BCD 8421 may also be referred to as Natural BCD (NBCD) or Simple BCD (SBCD).

BCD 8421 is said to be a 'weighted code' because each of its columns has a weight associated with it. Similarly, BCD 2421 is also a weighted code, although in this case the weight of the most-significant bit (MSB) is $2^1 = 2$. By comparison, Excess-3, which is generated by adding 0011 (3 in decimal) to the encodings used in BCD 8421 is not a weighted code because it isn't possible to assign weights to the columns in such a way that they add up to their corresponding decimal values.

For the remainder of our discussions, and for our experiments, we will be employing BCD 8421. Before we proceed, however, can you spot anything interesting with respect to BCD 2421 and Excess-3 (some characteristic they share with each other but not with BCD 8421)? The answer is given at the end of this column.

Then and now

When people first started to build electromechanical and electronic digital computers in the 1940s, binary techniques were not widely understood. Since people were so comfortable using decimal, it seemed to make sense to implement computers as decimal machines. What this means is that computers like the ENIAC, IBM NORC, and UNIVAC Solid State 80 represented and manipulated numbers and addresses in decimal without converting them to pure binary equivalents.

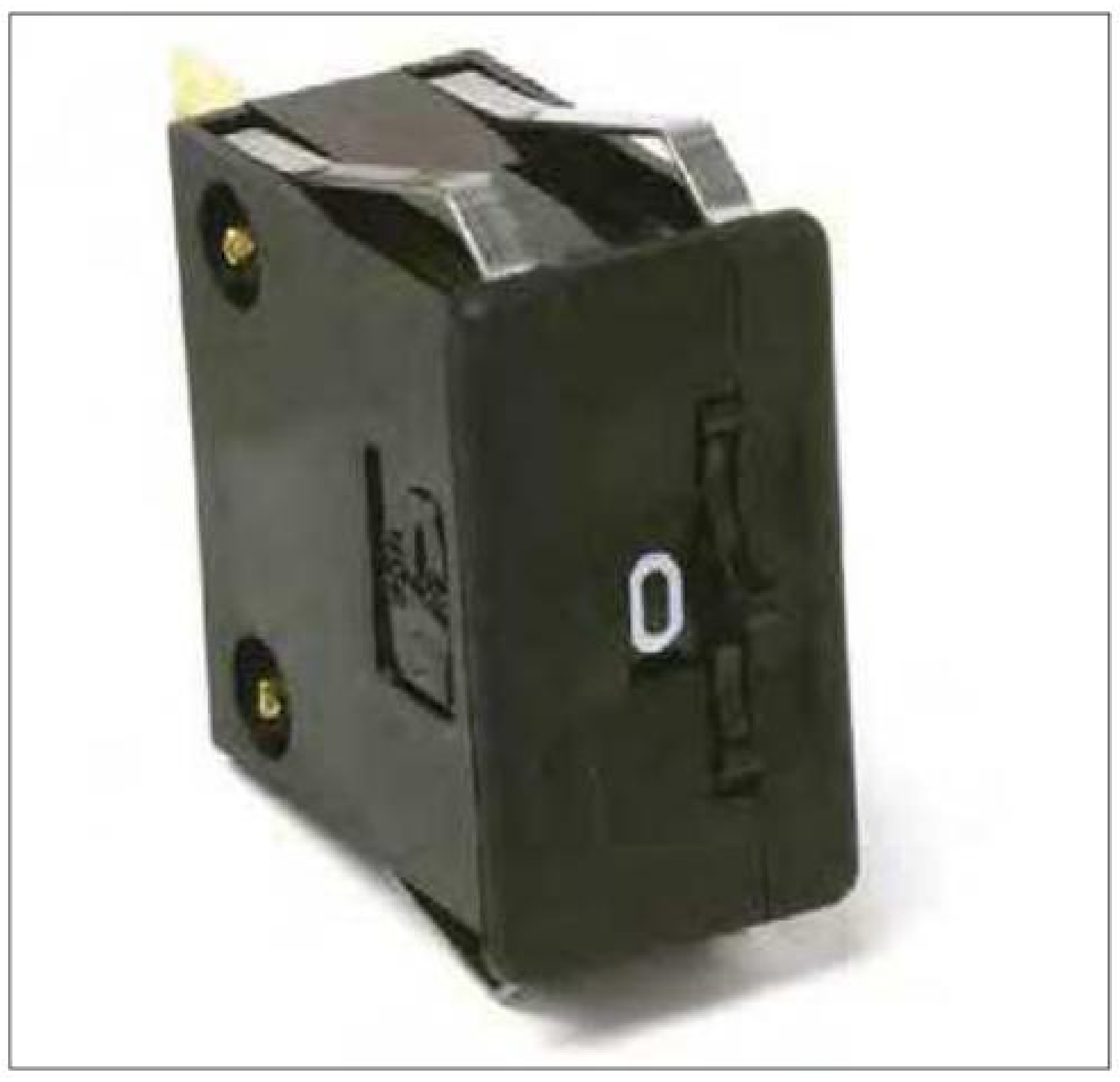


Fig.3. A 302109000 BCD thumbwheel switch (Source: C&K)

It didn't take long before computer scientists started to recognise the inherent advantages associated with binary machines. Having said this, BCD continues to be used much more than you might expect. One example is to allow operators in industrial facilities to easily specify decimal values using BCD thumbwheel switches, such as the 302109000 from C&K shown in Fig.3 – see: **https://bit.ly/3RaO0uY**

Rotating the thumbwheel on the front causes the corresponding BCD 8421 code to be presented on four terminals at the rear. By mounting groups of these switches together, users can specify larger numerical values.

Another way in which BCD is used today is to drive 7-segment light-emitting diode (LED)-based displays like the one we are currently using in our experiments (Fig.4).

What a character!

Before we proceed further, we need to decide which segment combinations we wish to use to represent the numbers 0

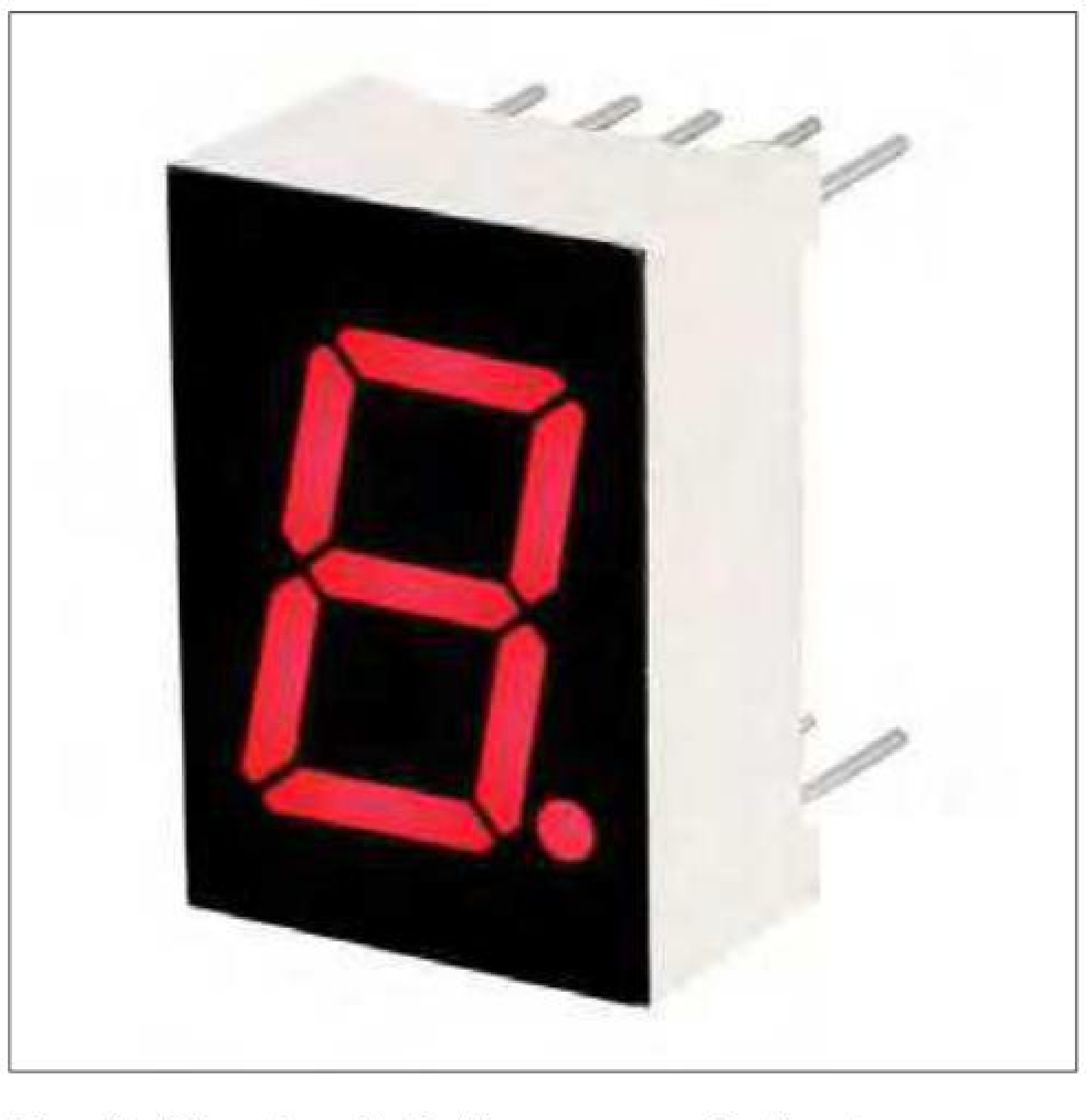


Fig.4. Single-digit 7-segment display.

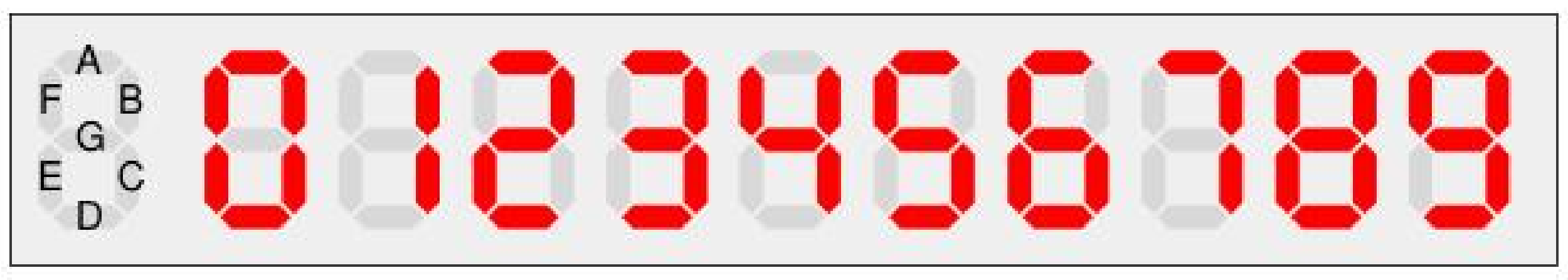


Fig.5. Segments used to represent 0 through 9.

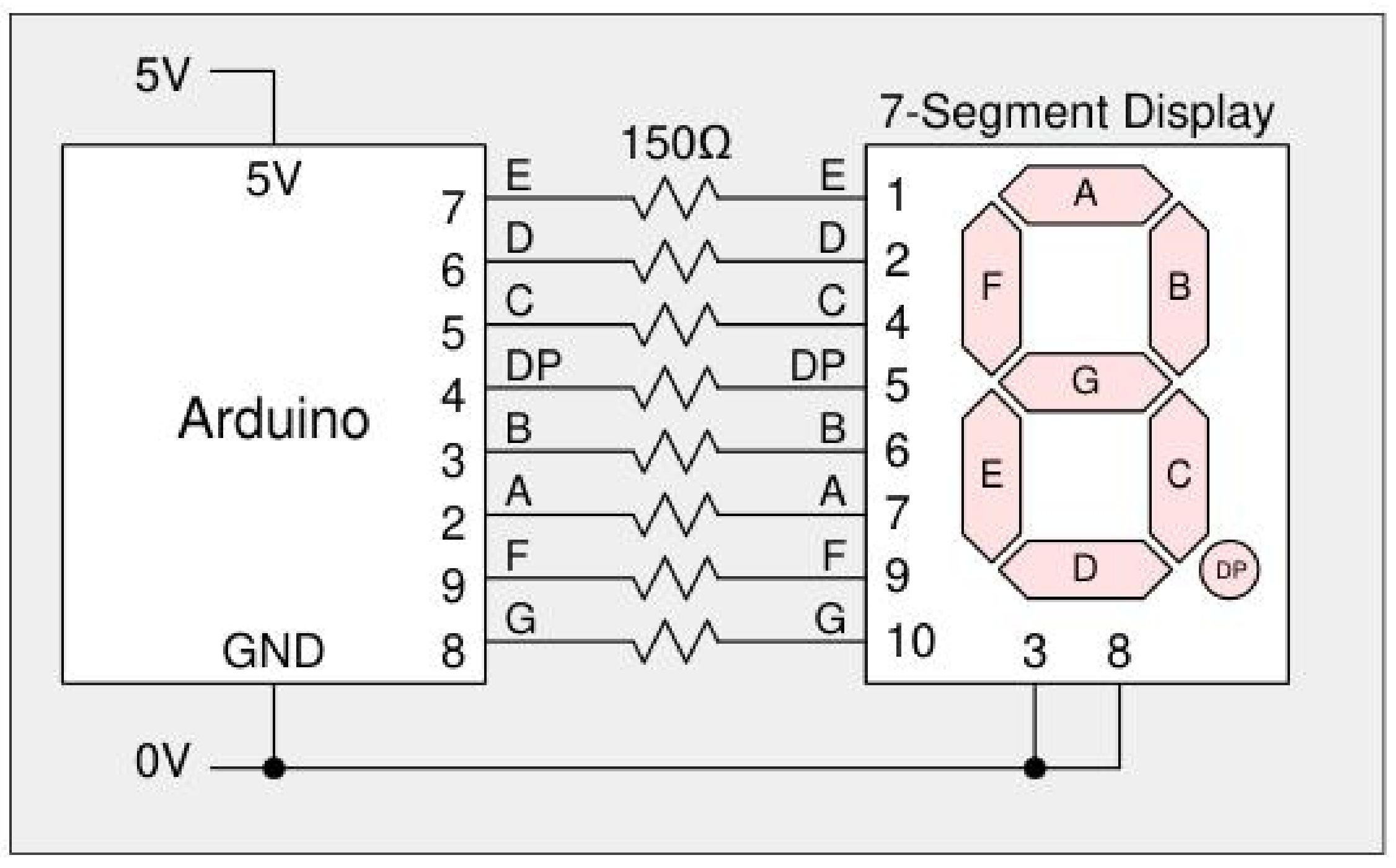


Fig.6. Using 8 pins to drive a 7-segment display.

through 9 (Fig.5). Although this seems strange, there is no standard for this sort of thing by any relevant entity, such as the IEC, IEEE, or ISO, which means we are obliged to come up with our own.

For example, we are using segments B and C to represent the number 1, which is the most common scenario, but there is nothing to stop us using segments E and F if we wish. Similarly, we've included segment A in our representation of 6 and segment D in our representation of 9, while some may consider the use of these segments in these cases to be superfluous to requirements.

Hardware BCD decoders

So, why have I been waffling on about BCD? Well, we are currently using eight of our Arduino Uno's digital output pins to drive our single-digit common cathode 7-segment display (Fig.6).

Suppose we were pin-limited, and we couldn't afford to dedicate eight pins to this task. One solution would be to purchase a BCD-to-7-segment decoder integrated circuit (IC). We could drive this decoder using just four of our Arduino's pins, leaving the decoder to control the segments on the display (Fig.7).

We should note that a decoder of this type doesn't drive the display's decimal point (DP) segment, which would require its own control. This is because only one decimal point is typically required when using a group of such displays. The only reason we've shown greyed-out 0 values associated with the DP column in the truth table in Fig.7 is to match what we are going to discuss in a moment.

Software BCD decoders

We will be using hardware BCD decoders in future columns when we start to employ multiple 7-segment digits in our projects. For the moment, however, we are going to implement a pseudo-BCD decoder in software.

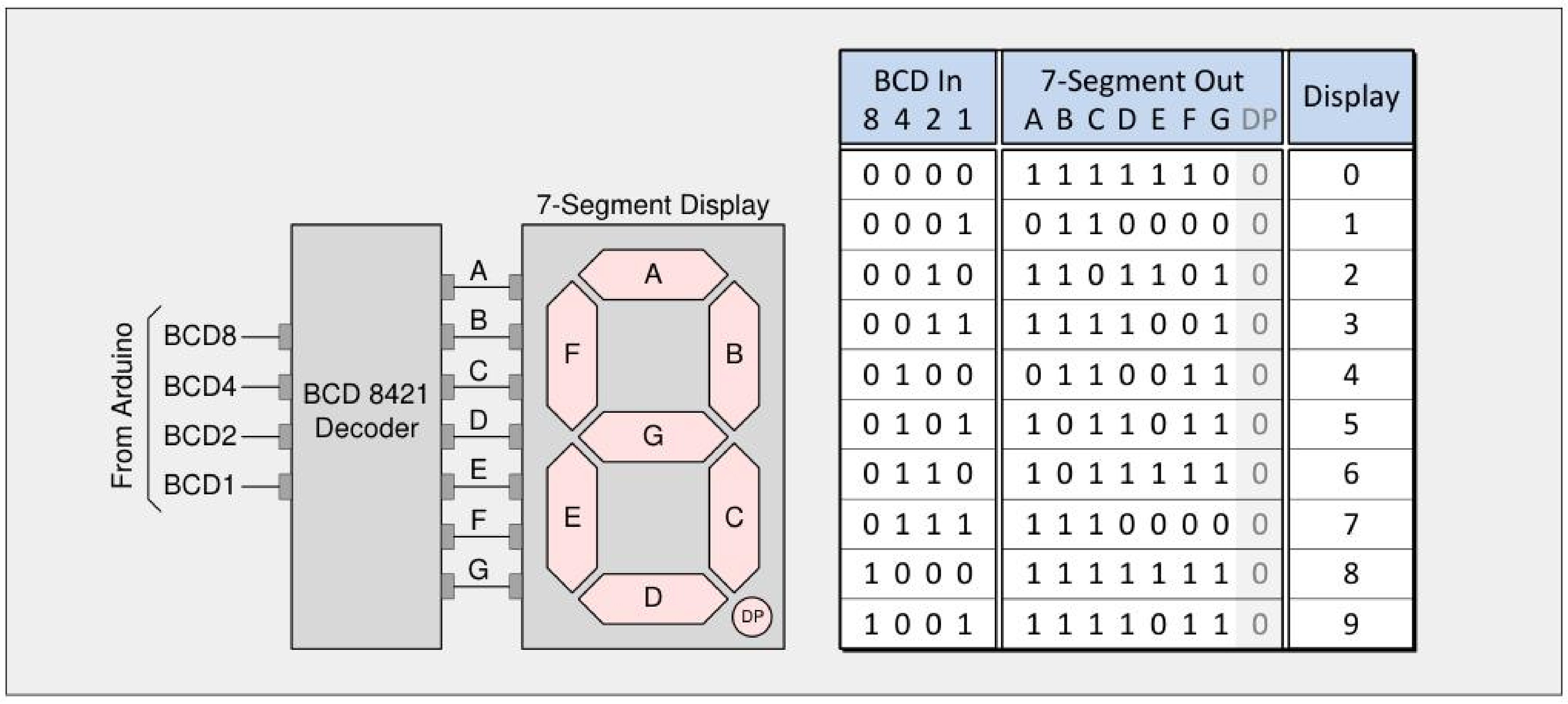
We are currently using Arduino pins 2, 3, 5, 6, 7, 9, 8 and 4 to drive display segments A, B, C, D, E, F, G, and DP, respectively (Fig.6). A word of warning… don't do what I just did, which is to mistakenly used the numbers from the 7-segment display in my pin array so that my program didn't work. It took me ages to figure it out and caused me some consternation... eventually driving me to exclaim 'Oh Dear' (or words to that effect).

In *Part 3*, we experimented with a red-green LED combo, but we won't be needing that anymore, so you can remove those components from your breadboard. All we expect to see on the breadboard now are our main power LED, our 7-segment display, and any associated current-limiting resistors.

Our current breadboard layout, including connections to our Arduino Uno, was shown in *Part 3*. If you don't happen to have that issue close to hand (for shame!), you can download a copy of this layout (file **CB-Apr23-01.pdf**).

In our previous programs, we defined `SEG_ON` as being `HIGH` and `SEG_OFF` as being `LOW`. Bearing this in mind, if we wished to display the number 5, for example, we could do so using the following statements:

```
digitalWrite(2, SEG_ON);  // A
digitalWrite(3, SEG_OFF); // B
digitalWrite(5, SEG_ON);  // C
digitalWrite(6, SEG_ON);  // D
digitalWrite(7, SEG_OFF); // E
digitalWrite(9, SEG_ON);  // F
digitalWrite(8, SEG_ON);  // G
digitalWrite(4, SEG_OFF); // DP
```



BCD In 8 4 2 1	7-Segment Out A B C D E F G DP	Display
0 0 0 0	1 1 1 1 1 1 0 0	0
0 0 0 1	0 1 1 0 0 0 0 0	1
0 0 1 0	1 1 0 1 1 0 1 0	2
0 0 1 1	1 1 1 1 0 0 1 0	3
0 1 0 0	0 1 1 0 0 1 1 0	4
0 1 0 1	1 0 1 1 0 1 1 0	5
0 1 1 0	1 0 1 1 1 1 1 0	6
0 1 1 1	1 1 1 0 0 0 0 0	7
1 0 0 0	1 1 1 1 1 1 1 0	8
1 0 0 1	1 1 1 1 0 1 1 0	9

Fig.7. Using a BCD-to-7-segment decoder IC.

Eeek! That's eight lines of code, which means we would require 80 lines to cover all 10 of our digits. And that's just the beginning. Suffice it to say that using this approach to control our display would not be pretty, efficient or fun.

As an alternative, the approach we are going to use is to create a pseudo-BCD decoder in the form of a look-up table. Do you recall earlier in this column where we noted that a common 8-bit grouping is called a byte? Well, the Arduino environment supports a `byte` data type (the equivalent generic C/C++ data type would be `unsigned char`). This data type can represent unsigned (positive) integers in the range 0 to 255 in decimal, 00000000 to 11111111 in binary, or 00 to FF in hexadecimal, which is a number system we have yet to introduce. We will discuss hexadecimal in *Part 5*. For now, we indicate hexadecimal values in C/C++ by prefixing them with '0x'.

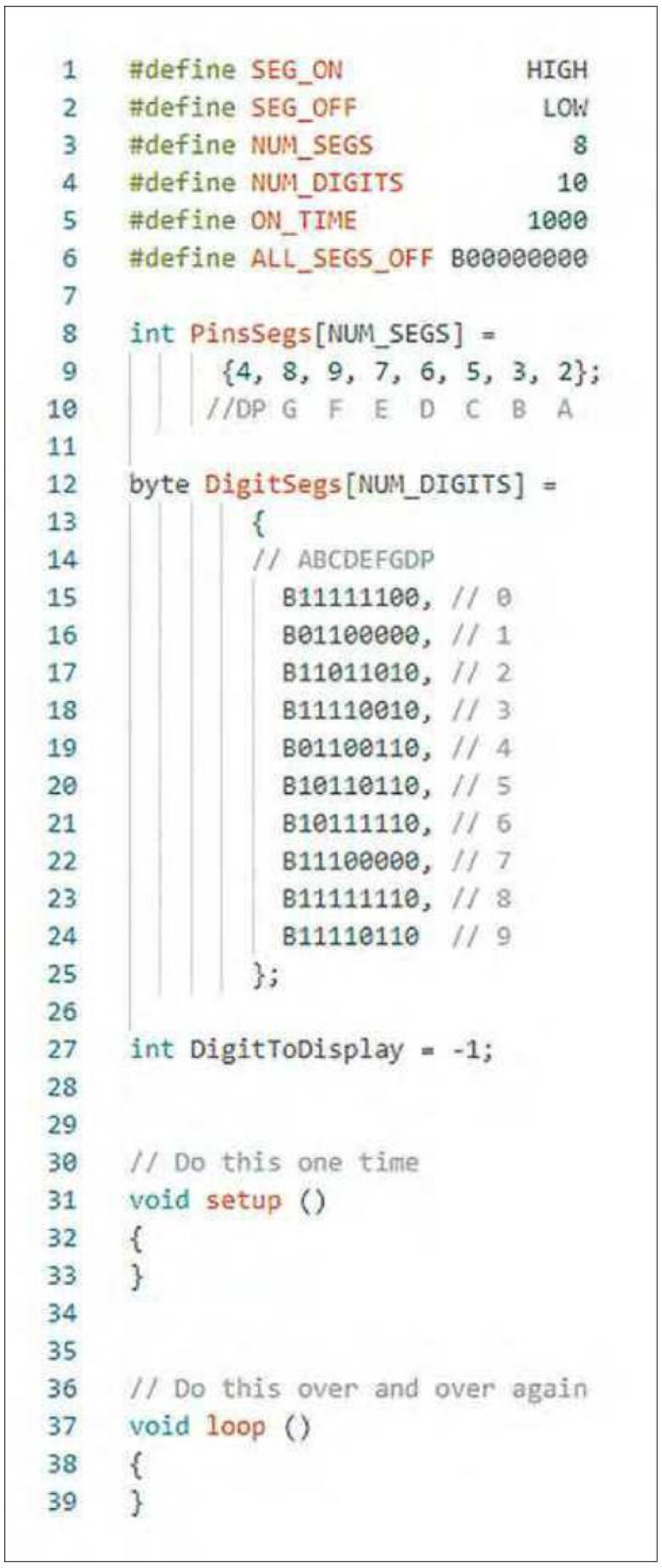
We can assign positive integer values (eg, 42) and hexadecimal values (eg, 0x2A) to variables of the `byte` data type. Also, unlike regular C/C++ environments, we can assign 8-bit binary values prefixed by the letter 'B' (eg, `B00101010`). Assuming we've defined `NUM_DIGITS` to be 10, this allows us to create our look-up table as follows (remember that anything to the right of // is understood by the compiler to be a comment):

```
byte DigitSegs[NUM_DIGITS] =
   {
   // ABCDEFGDP
      B11111100, // 0
      B01100000, // 1
      B11011010, // 2
      B11110010, // 3
      B01100110, // 4
      B10110110, // 5
      B10111110, // 6
      B11100000, // 7
      B11111110, // 8
      B11110110  // 9
   };
```

Compare these bit patterns to those illustrated in Fig.7. In particular, observe that we've included the 0s associated with the DP segment. We were obliged to do this to fully pack our 8-bit byte fields, even though we don't plan on using the DP segment at the moment.

Bare bones

The way I usually set about building a new application is to spend a little time thinking about what I want to do and then creating a skeleton program. In this case, we want a program that will display our decimal digits for one second at a time, but we also want to be able to vary the order in which the digits will be displayed (you'll see what I mean by this a little later).



```
#define SEG_ON          HIGH
#define SEG_OFF          LOW
#define NUM_SEGS           8
#define NUM_DIGITS        10
#define ON_TIME         1000
#define ALL_SEGS_OFF B00000000

int PinsSegs[NUM_SEGS] =
      {4, 8, 9, 7, 6, 5, 3, 2};
      //DP G  F  E  D  C  B  A

byte DigitSegs[NUM_DIGITS] =
      {
      // ABCDEFGDP
        B11111100, // 0
        B01100000, // 1
        B11011010, // 2
        B11110010, // 3
        B01100110, // 4
        B10110110, // 5
        B10111110, // 6
        B11100000, // 7
        B11111110, // 8
        B11110110  // 9
      };

int DigitToDisplay = -1;


// Do this one time
void setup ()
{
}


// Do this over and over again
void loop ()
{
}
```

Listing 1. Skeleton program.

My first step would be to create the bare bones program shown in Listing 1. As usual, we start with some of the definitions we'll be using (we may add to these later). From *Part 3*, we know that `NUM_SEGS` defines the number of segments in the display as being 8. We've added `NUM_DIGITS` to define the number of digits we wish to display as being 10. We're going to use the `ON_TIME` definition to display the current digit for one second. And I'd like to think that the `ALL_SEGS_OFF` definition is self-explanatory.

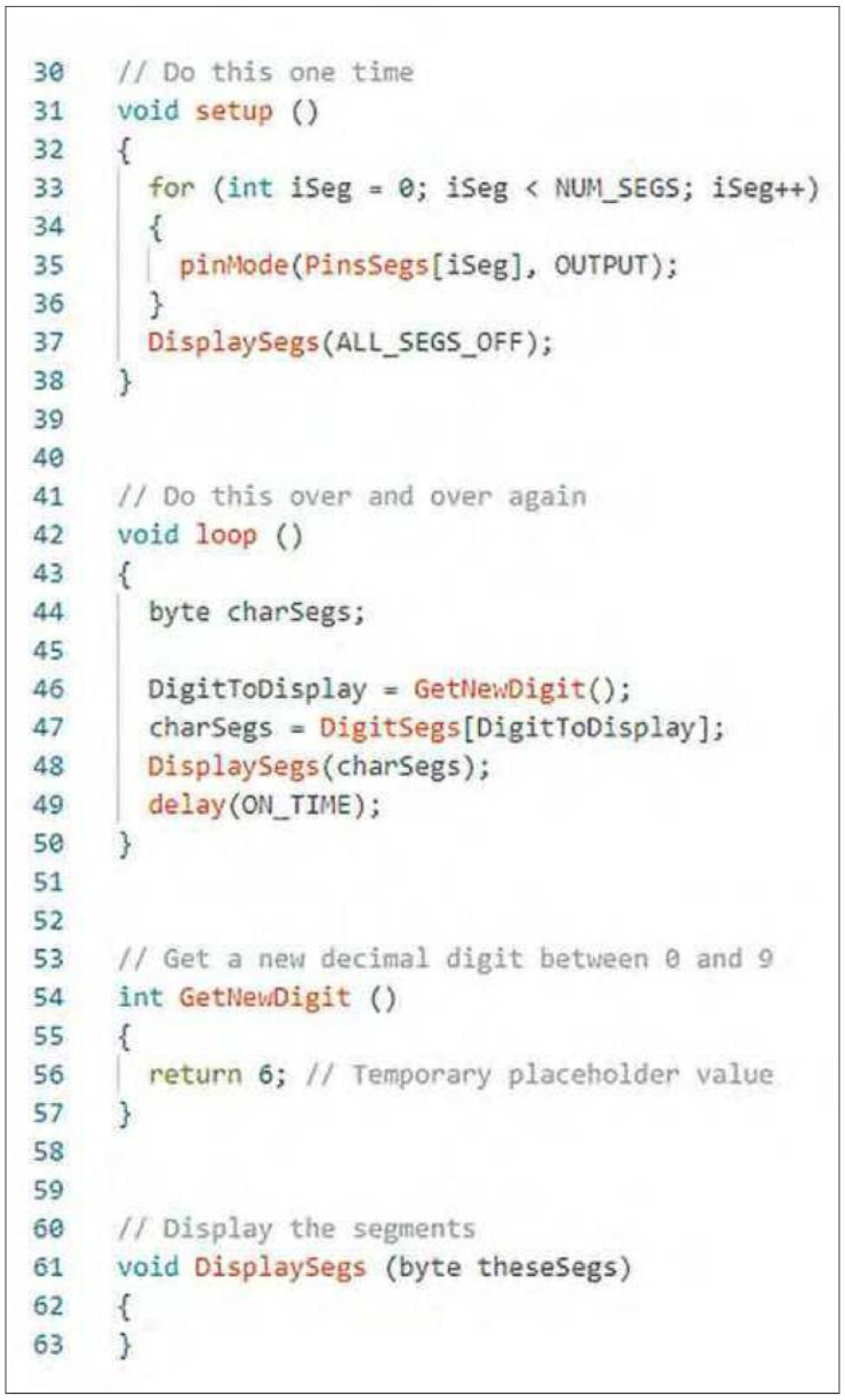
Observe the `PinsSegs[]` array declaration. We use this to assign the Arduino pins we're going to use to drive the eight segments in our 7-segment display (remember that DP is considered to be a segment). If you compare this to our programs from *Part 3*, you'll see that we've reversed the order of the pin assignments. This time, we're starting with pin 4, which drives the DP segment, and we're ending with pin 2, which drives the A segment. The reason we're doing things this way will become clear as we proceed.

In addition to our `DigitSegs[]` look-up table, we also declare an integer variable called `DigitToDisplay` to which we assign a value of –1. The reason for using this –1 value was introduced in *Part 3*, and we discuss it again later in this column.

This would be a great time for us (well, you) to enter the contents of Listing 1 into your Arduino IDE. Once you've done so, it's a good idea to click the Verify icon (or use the Sketch > Verify/Compile command) to make sure our skeleton program compiles without errors. It's a lot easier to sort any problems out now before we add more code to confuse the issue.

Fleshing things out

Now we're going to flesh things out a little. Let's start by summarising what we know about functions. The simplest definition is that a *function is a group of statements that perform a task*. We've already had some experience with these little scamps in the form of the mandatory `setup()` and `loop()` functions, which the Arduino's IDE automatically inserts into our programs. We've also noted that the IDE includes a wealth of built-in functions, such as the `pinMode()`, `digitalWrite()` and `delay()` functions we've employed in previous programs. Now we're going to create two functions of our own. We'll call these functions `GetNewDigit()` and `DisplayNewDigit()`, as illustrated in Listing 2.



```
// Do this one time
void setup ()
{
  for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
  {
    pinMode(PinsSegs[iSeg], OUTPUT);
  }
  DisplaySegs(ALL_SEGS_OFF);
}


// Do this over and over again
void loop ()
{
  byte charSegs;

  DigitToDisplay = GetNewDigit();
  charSegs = DigitSegs[DigitToDisplay];
  DisplaySegs(charSegs);
  delay(ON_TIME);
}


// Get a new decimal digit between 0 and 9
int GetNewDigit ()
{
  return 6; // Temporary placeholder value
}


// Display the segments
void DisplaySegs (byte theseSegs)
{
}
```

Listing 2. Fleshing things out a little.

Before we consider the code with which we're going to populate these functions, there are several points that are worthy of note. Let's start with the fact that, in addition to using an initial capital letter for my global variable names, I also use an initial capital letter for my function names because I think of them as being global entities (we can't do anything about the names of the Arduino IDE's built-in functions).

Remember that C/C++ doesn't care about our use of whitespace characters. Having said this, when I *declare* a function, I include a space between the name and its parentheses, like `GetNewDigit ()`, for example. By comparison, when I *call* a function from elsewhere in the program, I omit this space, like `GetNewDigit()`, for example. The reason for doing this is that it facilitates using the editor to search for *calls* to a function versus the *declaration* of that function.

In previous columns, I've used the term 'argument' and qualified this by saying 'think parameter,' but now it's time to delve a little deeper. When we declare a function, part of this declaration is a comma-separated list of *parameters* in parentheses. In the case of our `DisplaySegs()` function, for example, we have one parameter of type `byte` called `theseSegs`.

By comparison, when we call a function, like our call to `DisplaySegs()` from within our `loop()` function, we pass in a comma-separated list of *arguments* in parentheses. In this case, we are passing in a single argument of type `byte` called `charSegs`.

Of course, if a function is declared with an empty parameter list, then, when we call it, we will pass in an empty argument list (in both cases we keep the parentheses).

As I mentioned in a previous column (*PE*, October 2020): 'In the real world, a lot of people use the terms parameters and arguments interchangeably. So long as the person you are talking to understands the message you are trying to convey, then there's 'no harm, no foul,' as they say. The problem comes when you are talking with professional programmers who will take great delight in painstakingly instructing you in the error of your ways. Personally, I don't care to give the little rascals the satisfaction.'

Have you ever wondered why the `setup()` and `loop()` function declarations are prefixed by the `void` keyword (similarly for our new `DisplaySegs()` function)? Well, in the same way that we specify a data type when we declare a variable, we also specify a data type when we declare a function. In the case of functions that don't return any values, we use `void` as a data type that represents no data.

Now consider our new `GetNewDigit()` function. Instead of `void`, we've declared this as being of type `int`. This allows us to use the function to return an integer value by means of a `return` statement located at the end of the function (I'm simplifying things a little, but the gist is there).

Now look at the `DigitToDisplay = GetNewDigit()` statement in our `loop()` function. What this says is that whatever value is returned from the `GetNewDigit()` function call will be assigned to our `DigitToDisplay` variable.

I know that this can all seem to be a little overwhelming at first, but it won't take long before it's second nature to you. I should also point out that some of the code we are using here is a little 'clunky,' but we're doing things this way to provide us with examples to talk about.

Apart from the contents of our new functions, the rest of the program is complete. The `setup()` function, which – because of the way the Arduino's IDE does things – will be executed only one time, uses a `for()` loop to declare the pins we want to drive our display as being of type `OUTPUT` (we introduced `for()` loops in *Part 2* and *Part 3*). The `setup()` function also calls our `DisplaySegs()` function to turn all the display's segments off.

Contrariwise, because of the way the Arduino's IDE does things, the `loop()` function will be executed over and over. This function calls our `GetNewDigit()` function, which we will use to generate the next digit we wish to display. We use this returned value as an index into our `DigitSegs[]` array to retrieve the entry associated with the digit we wish to display. We then pass this value into our `DisplaySegs()` function, whose job it will be to turn the appropriate segments On and Off.

Before we proceed, this would be a good time to add these new statements to your program and then verify that this fleshed-out version compiles without errors.

Questions, questions

We are now poised to use a new form of control statement called `if()`, which essentially asks a question. The simplest form of this statement is as follows:

```
if (someCondition)
{
   // Do stuff
}
```

We discussed conditions and the concepts of `true` and `false` in toe-curling detail in *Part 3*. In this case, if the evaluation of `someCondition` returns `true`, then we will execute the statements inside the curly brackets. Alternatively, if the test returns `false`, we will skip everything inside the curly brackets and move onto the next statement.

A slightly more sophisticated version of this statement includes an `else` clause as follows:

```
if (someCondition)
{
   // Do stuff
}
else
{
   // Do other stuff
}
```

Once again, if the evaluation of `someCondition` returns `true`, then we will execute the statements inside the curly brackets associated with the `if`. Alternatively, if the test returns `false`, then we will skip everything inside the curly brackets associated with the `if`, and instead execute the statements inside the curly brackets associated with the `else`.

But wait, there's more, because we can also associate a new `if` with an `else` as follows:

```
if (someCondition)
{
   // Do stuff
}
else if (anotherCondition)
{
   // Do other stuff
}
```

We can keep on adding more `else-if` constructs and we can end everything with a final `else` if we so desire.

If there's only one statement inside any of the pairs of curly brackets, then we can omit that pair of brackets and just use the statement on its own. For example:

```
if (someCondition)
   DisplaySegs(AllSegsOff);
```

Having said this, I strongly recommend that you always use a pair of curly brackets, even if they currently embrace only a single statement. There are two reasons for this. First, they make it easier to read and understand your code. Second, they prevent your introducing errors if you add more statements later, which is often the case when you are debugging a program and trying to determine why it's not doing what you expect it to do.

The &, | and ^ bitwise operators

As we've previously noted, computers are constructed out of simple logical building blocks. These are often called primitive gates, primitives, logic gates, or gates. The reason for the 'gate' moniker is that, in the same way a wooden gate can allow or prevent the passage of a person or an animal through an opening, so a logic gate can allow or prevent the passage of signals.

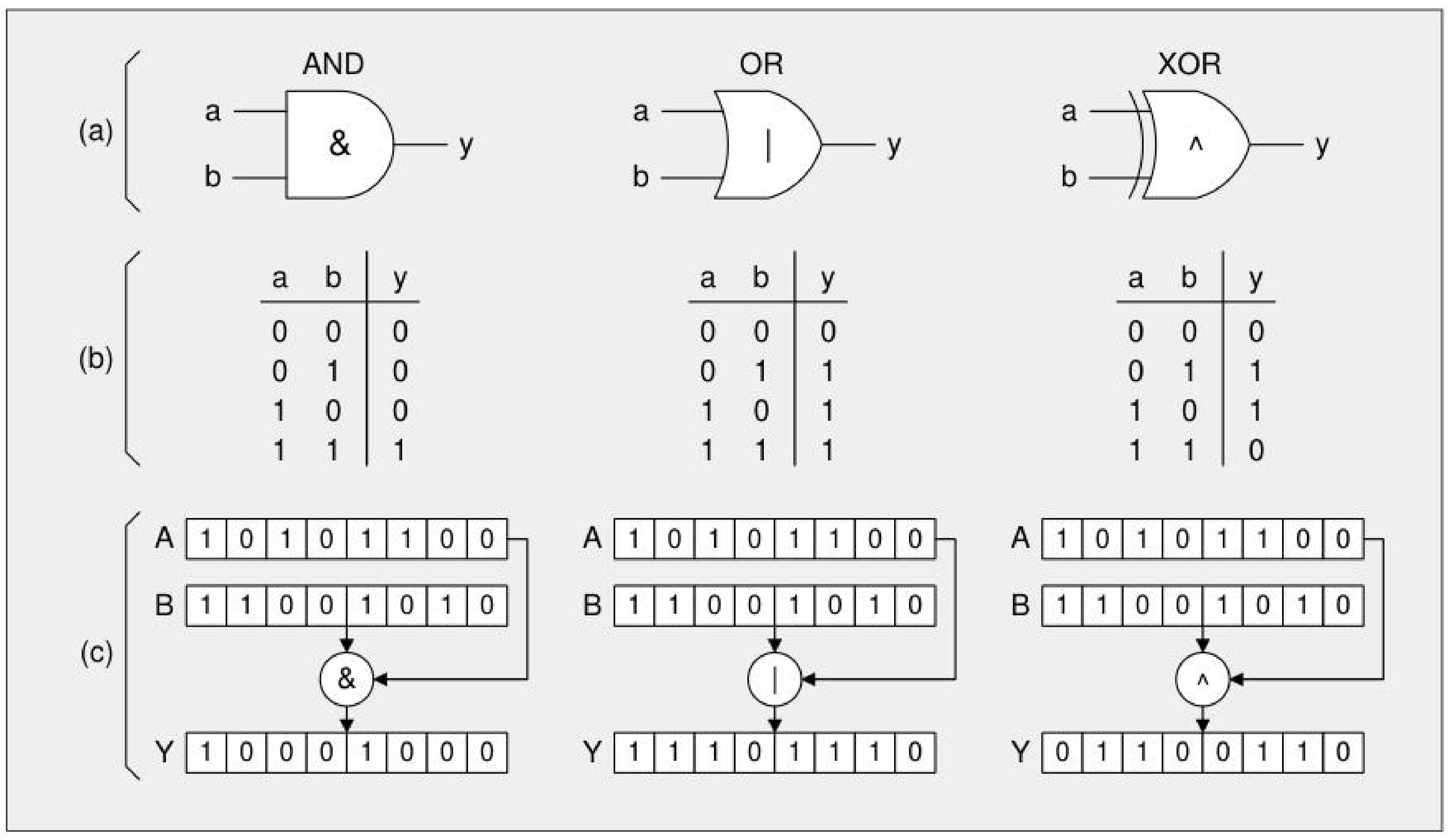


Fig.8. AND, OR and XOR functions: (a) Logic gate symbols, (b) Truth tables and (c) Examples of bitwise operators applied to two 8-bit bytes.

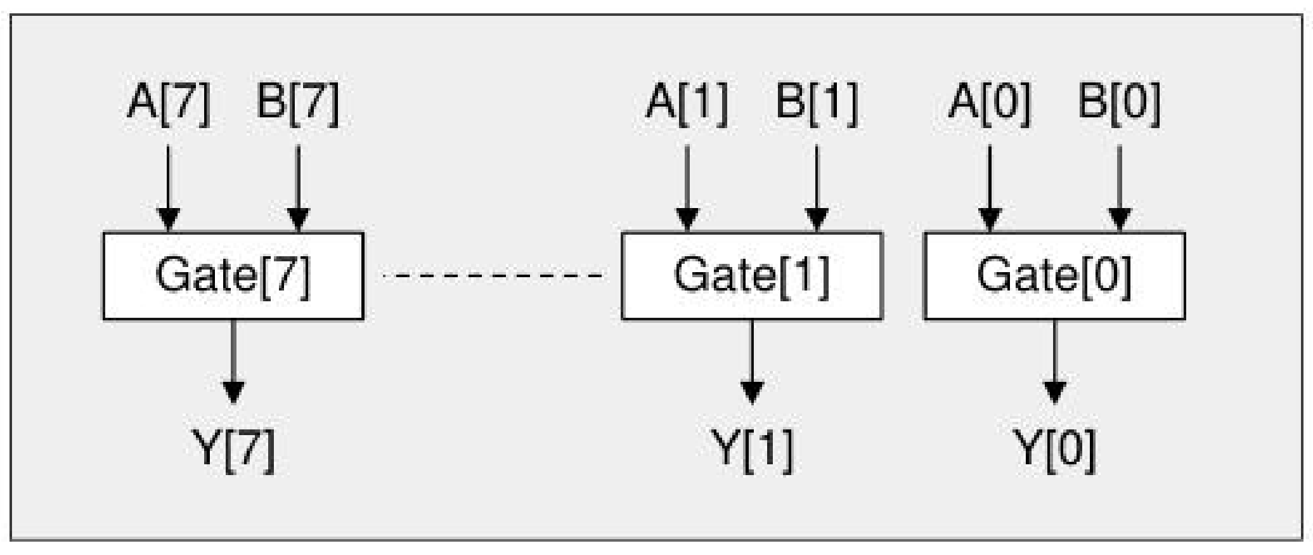


Fig.9. How the bitwise operators are realised in logic gates.

Three of the most common gates are the AND, OR, and XOR (Fig.8). These gates accept bit-size values on their inputs and generate bit-sized values on their outputs. If you want to know how these little rapscallions can be constructed out of transistors, this topic is discussed in ~~excruciating~~ exhilarating detail in my book *Bebop to the Boolean Boogie* – see: **https://amzn.to/3X0rF4i**

The symbols for these gates are shown in Fig.8a. Their corresponding truth tables are presented in Fig.8b. Observe that the output from the AND gate is 1 (true) only when both of its inputs are 1, otherwise the output is (0) false. By comparison, the output from the OR gate is 1 if either of its inputs are 1. Although we rarely do so, the OR gate is more properly referred to as an 'inclusive OR' because the output being 1 *includes* the case where both the inputs are 1. By comparison, with an exclusive OR (XOR) gate, the output being 1 *excludes* the case where both the inputs are 1.

In *Part 3* of this epic saga, we introduced the conditional operators `&&` (AND) and `||` (OR). The reason we call these conditional operators is that we use them as part of condition statements. For example, assuming `a`, `b`, `c`, and `d` to be integer variables, we could have a condition like `(a > b) && (c < d)`, which we can think of as 'a is greater than b AND c is less than d.' The output of this condition will only return `true` if *both* sub-conditions are `true`. Similarly, we could have a condition like `(a > b) || (c < d)`, which we can think of as 'a is greater than b OR c is less than d.' The output of this condition will return `true` if *either* of the sub-conditions are `true`.

Now, this is where we take tentative steps into new territory because we can also use `&`, `|` and `^` as bitwise operators. The easiest way to visualise what this means is to assume that we've declared three variables of type `byte` called `A`, `B` and `Y`. Now, suppose we use the bitwise operators in a program as follows:

```
Y = A & B; // Bitwise AND
Y = A | B; // Bitwise OR
Y = A ^ B; // Bitwise XOR
```

Since we are using bitwise operators on variables of type `byte`, and since bytes contain eight bits, this is equivalent to feeding our `A` and `B` values into eight 2-input gates. The processor will perform the selected operation between each bit forming `A` and the corresponding bit forming `B` (Fig.9). In the case of the `&` operator the gates will be AND gates, in the case of the `|` operator they will be OR gates, and in the case of the `^` operator they will be XOR gates. This is the way the central processing unit (CPU) in our microcontroller implements these operators; that is, by using real, physical logic gates.

Suppose we previously assigned binary values of 10101100 and 11001010 to variables `A` and `B`, respectively. In this case, the results from using the bitwise operators will be as illustrated in Fig.8c.

These operators work with `byte` variables (which are always unsigned), `char` variables (signed or unsigned), and `int` variables (short, regular, long; signed or unsigned), the only rule being that all the variables (input and output) must be of the same type.

Using masks

One thing the bitwise operators can be used for is creating and applying masks. Suppose we have a variable of type `byte` called `A`, but we don't know its contents. Now suppose we want to determine the contents of the least-significant four bits of `A`. We could extract these bits using a bitwise `&` as follows:

```
Y = A & B00001111;
```

In this case, the binary value 00001111 is our mask. Remind yourself of the way an AND gate works (Fig.8a). The result of this operation will be to clear the most-significant four bits of `Y` to 0; meanwhile, the least-significant four bits of `Y` will end up as a copy of the least-significant four bits of `A`.

Remember that the bits forming an 8-bit byte are numbered from 0 (on the right) to 7 (on the left). Now suppose we want to force bit 2 (ie, the *third* bit) of `A` to 0 while leaving the other bits as-is. We could do so using a bitwise `&` as follows:

```
A = A & B11111011;
```

Contrariwise, suppose we wish to force bit 6 of `A` to 1 while leaving the other bits as-is. We could do so using a bitwise `|` as follows:

```
A = A | B01000000;
```

This is another point where things start to get interesting. Suppose we wish to perform some action if bit 3 of `A` is 0. We could achieve this using an `if()` statement with the following condition:

```
if ( (A & B00001000) == 0)…
```

In this case, the result from the bitwise `&` is temporary in nature. That is, it's not assigned to anything; it is used only as part of the test. The 0s in bits 0, 1, 2, 4, 5, 6, and 7 of our B00001000 value will force these bits in the temporary result to 0. Meanwhile, the 1 in bit 3 of our B00001000 value will allow whatever 0 or 1 is in the corresponding bit in `A` to appear in the temporary result, and it is this value that will be compared to 0.

I have a trick question. Suppose we wish to perform some action if bit 3 of `A` is 1. Look at the previous statement. Is your knee-jerk reaction to replace the `== 0` with `== 1`? It's not that easy, I'm afraid, because a 1 in bit 3 is 00001000 in binary, which is equivalent to 8 in decimal. But turn that frown upside down into a smile, because we can achieve the desired effect using the following statement:

```
if ( (A & B00001000) != 0)…
```

So, as opposed to thinking about this as 'Is the result one?' we instead think 'Is the result non-zero?' If you wish to dive deeper into the mysteries of masks, you will probably not be overly surprised to discover I've written a column on this very topic – see: **https://bit.ly/3Yd3UaS**

The << and >> shift operators

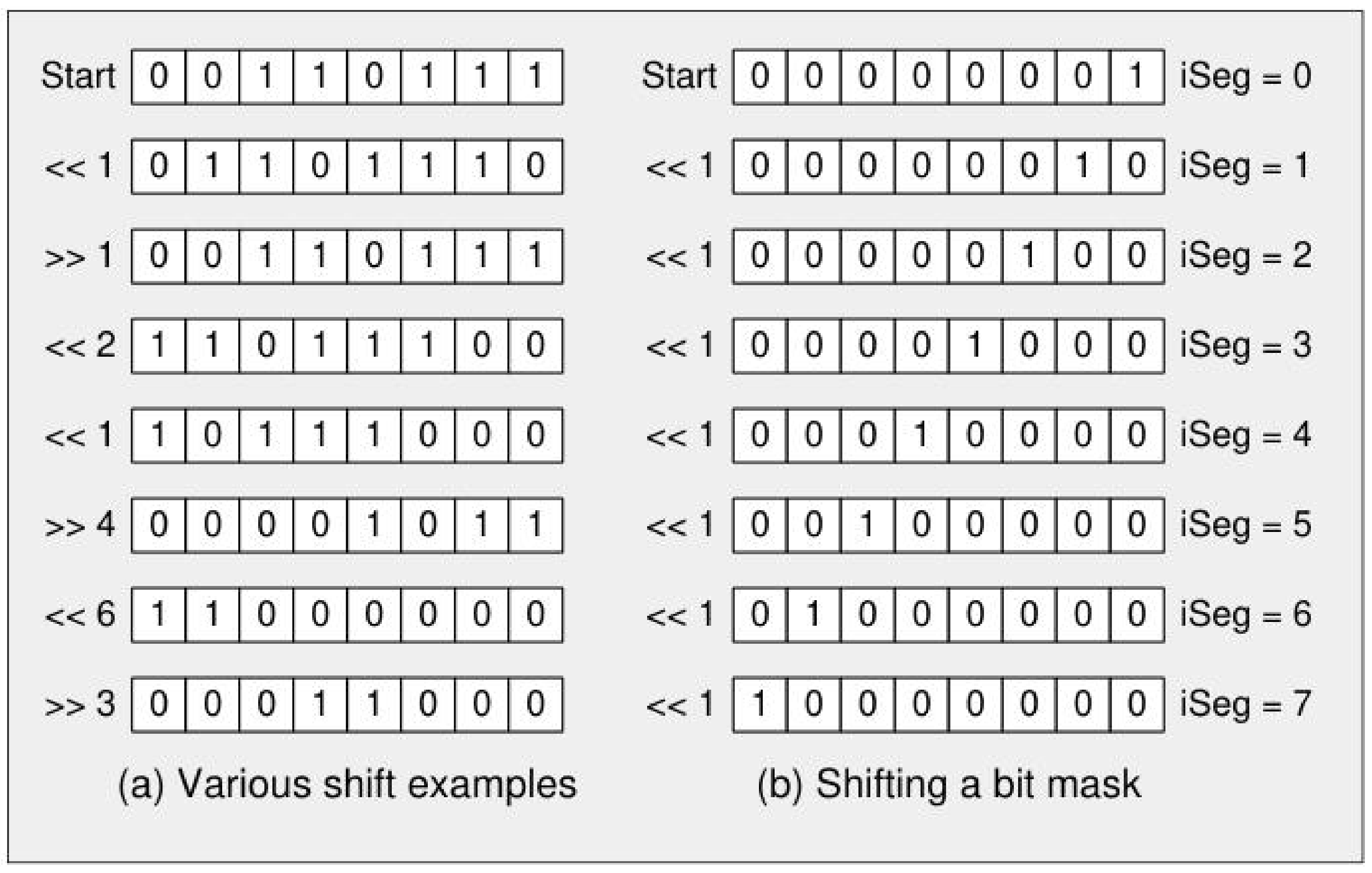
The C/C++ programming languages support two bitwise shift operators: the left-shift << and the right-shift >>. These operators require two operands – the first is the variable or value to be shifted, and the second (which can be a positive number or a variable of type `int` containing a positive value) specifies by how many bits the shift will involve. For example (assuming `A` is a variable of type `byte`):

```
Y = A << 1; // Shift A left 1 bit
Y = A >> 5; // Shift A right 5 bits
```

When a value is shifted left, the most-significant (left-hand) bit or bits effectively 'fall off the end.' Meanwhile, 0 values are shifted into the newly vacated right-hand bit or bits. This is known as a 'logical shift' and is true for both signed and unsigned values.

Similarly, when a value is shifted right, the least-significant (right-hand) bit or bits effectively 'fall off the end.' If the data being shifted is an unsigned `char` or `int` data type (the `byte` data type is unsigned by default), then the result is a logical shift, and 0 values will be shifted into the newly vacated left-hand bits (we'll leave what happens when performing shift-right operations on signed data types as a topic for another day).

Not surprising, shifting left or right by 0 bits has no effect. One interesting nugget of knowledge is the fact that shifting left

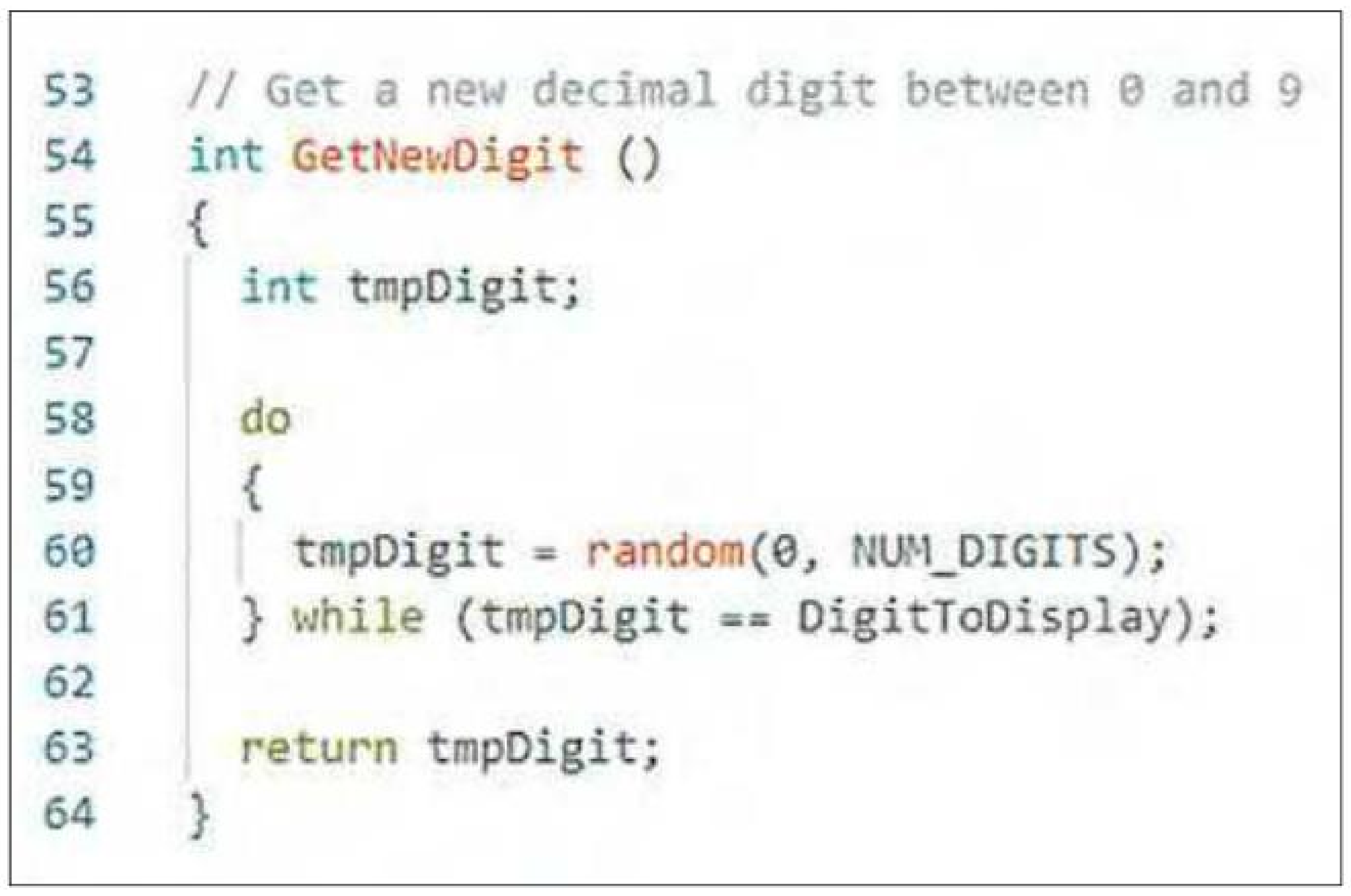


(a) Various shift examples	
Start	0 0 1 1 0 1 1 1
<< 1	0 1 1 0 1 1 1 0
>> 1	0 0 1 1 0 1 1 1
<< 2	1 1 0 1 1 1 0 0
<< 1	1 0 1 1 1 0 0 0
>> 4	0 0 0 0 1 0 1 1
<< 6	1 1 0 0 0 0 0 0
>> 3	0 0 0 1 1 0 0 0

(b) Shifting a bit mask		
Start	0 0 0 0 0 0 0 1	iSeg = 0
<< 1	0 0 0 0 0 0 1 0	iSeg = 1
<< 1	0 0 0 0 0 1 0 0	iSeg = 2
<< 1	0 0 0 0 1 0 0 0	iSeg = 3
<< 1	0 0 0 1 0 0 0 0	iSeg = 4
<< 1	0 0 1 0 0 0 0 0	iSeg = 5
<< 1	0 1 0 0 0 0 0 0	iSeg = 6
<< 1	1 0 0 0 0 0 0 0	iSeg = 7

Fig.10. (left) Performing shift operations on an 8-bit byte.

Listing 4 (right) Random version of `GetNewDigit()`



```
// Get a new decimal digit between 0 and 9
int GetNewDigit ()
{
  int tmpDigit;

  do
  {
    tmpDigit = random(0, NUM_DIGITS);
  } while (tmpDigit == DigitToDisplay);

  return tmpDigit;
}
```

by one bit is the same as multiplying by $2^1 = 2$. For example, shifting the value 00000110 (6 in decimal) left by one bit results in 00001100 (12 in decimal). Similarly, shifting left by two bits is the same as multiplying by $2^2 = 2 \times 2 = 4$; shifting left by three bits is the same as multiplying by $2^3 = 2 \times 2 \times 2 = 8$, and so forth. Contrariwise, shifting right by one bit is the same as dividing by 2; shifting right by 2 bits is the same as dividing by 4, and so on.

In the not-so-distant past, knowing this sort of thing used to be extremely useful when working with simple, resource-limited processors like the Arduino Uno – and it can still come in handy on occasion – but today's compilers are very clever, and they will automatically take full advantage of these tricks without you having to worry about things.

The shift operators work with `byte` variables, `char` variables (signed or unsigned) and `int` variables (short, regular, long; signed or unsigned). A series of examples of various shifts performed on a `byte` variable are illustrated in Fig.10a (read this sequence from top to bottom).

Bringing it all together

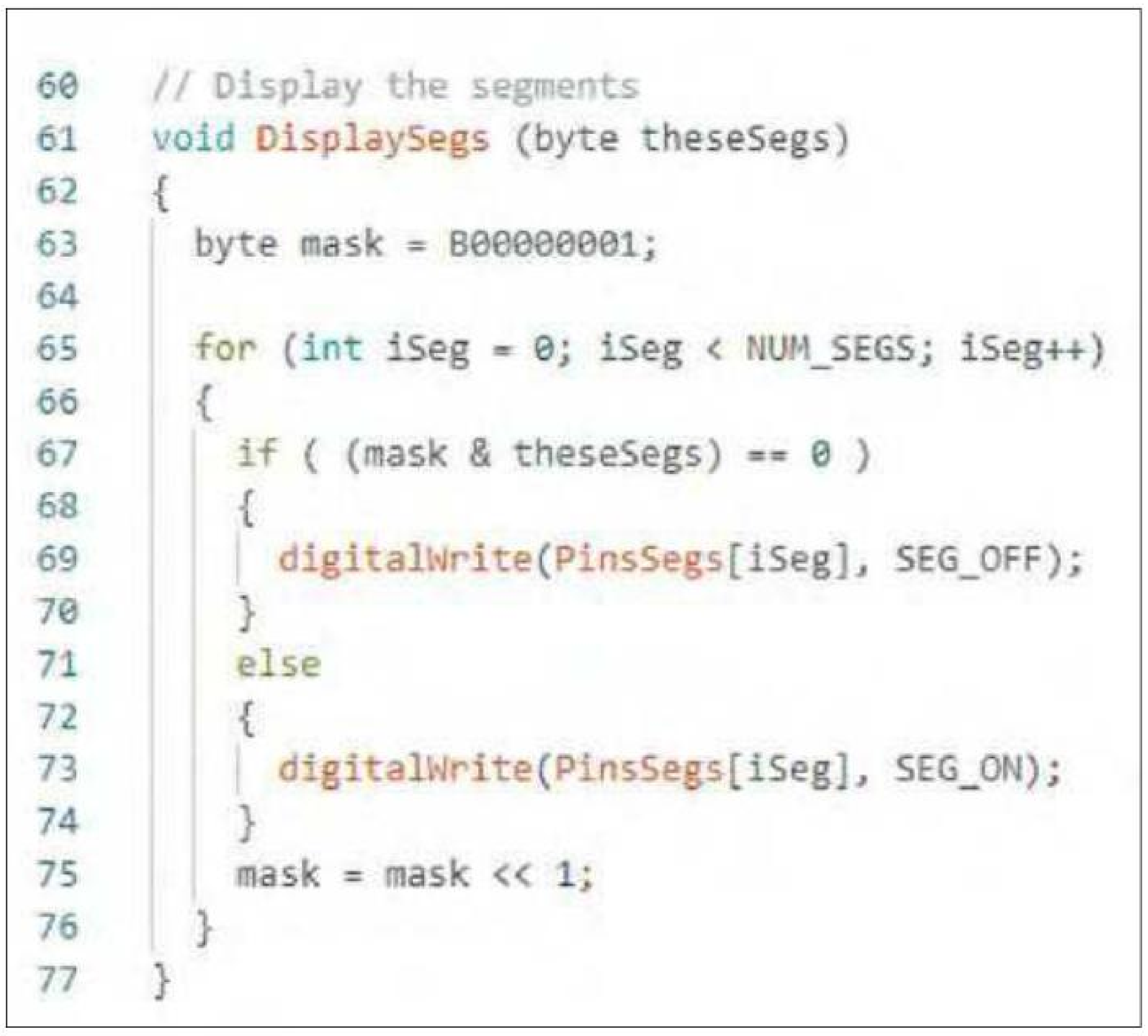
Let's leave our `GetNewDigit()` function for the moment and instead focus on our `DisplaySegs()` function. The way I've implemented this employs an `if()` statement, the use of a mask, a bitwise `&` (AND), and a bitwise << (shift left) as shown in Listing 3.

As we've already discussed, we pass an 8-bit byte into this function. The 0s and 1s in this byte, whose name is `theseSegs` inside the function, correspond to the segments we want to turn off and on, respectively. We start by declaring a variable called `mask` of data type `byte` and assigning it a value of `B00000001`.

The main body of this function involves a `for()` loop. The first thing we do inside this loop is to use the `&` operator to perform a bitwise AND between the `mask` and `theseSegs`, then we use an `if()` to compare the result to 0. If there's a 0 in `theseSegs` in the same bit position as the 1 in `mask`, then the result of this comparison will be `true`, in which case we turn the corresponding segment Off, otherwise we fall through to the `else` clause and turn the segment On.

The final statement in our `for()` loop shifts our mask one bit to the left. The way the values in the mask correspond to the values in our `iSeg` index variable is illustrated in Fig.10b.

Consider the way the 1 value slides through our mask from right to left, thereby testing the segments in the order DP, G, F, E, D, C, B, A. It now becomes apparent why we reversed the order of the Arduino pins driving the 7-segment display in our `PinsSegs[]` array declaration, because this makes things match up just the way we want them to.



```
// Display the segments
void DisplaySegs (byte theseSegs)
{
  byte mask = B00000001;

  for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
  {
    if ( (mask & theseSegs) == 0 )
    {
      digitalWrite(PinsSegs[iSeg], SEG_OFF);
    }
    else
    {
      digitalWrite(PinsSegs[iSeg], SEG_ON);
    }
    mask = mask << 1;
  }
}
```

Listing 3. Displaying the segments.

Add this code to your `DisplaySegs()` function and upload the program into your Arduino. If you run into any problems that you can't resolve, you can download my version (file **CB-Apr23-02.txt**).

Observe that the 7-segment display presents only the number 6. This isn't too surprising since all our `GetNewDigit()` function currently does is return the number 6. Now it's time to become more adventurous and start displaying all the numbers from 0 to 9 (I'm too young for all this excitement).

Tossing a coin

Can you cast your mind back to *Part 2* (*PE*, February 2023) when we created a program to randomly turn On and Off the segments in our 7-segment display? The problem was that we didn't include a test to see if the new random number was the same as the previous random number. This meant that, every now and then, a segment stayed on for some multiple of the expected time.

In *Part 3* (*PE*, March 2023), we implemented a solution that involved repeatedly generating new random numbers until we determined that the new value was different to the old value.

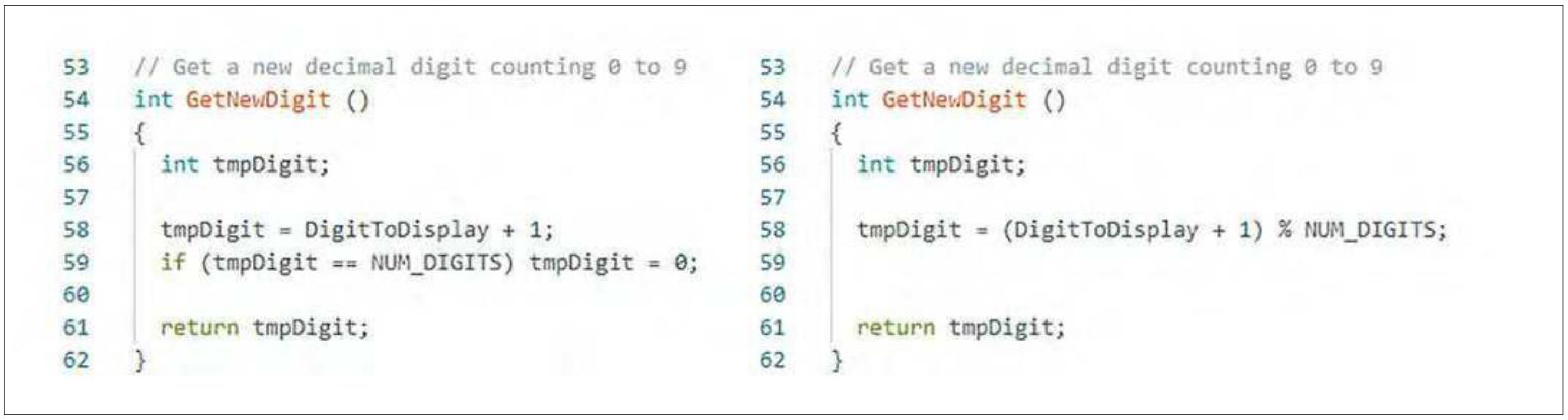
Now, I want you to see if you can add the code to our `GetNewDigit()` function to do something similar. This time, however, we want to randomly present numbers between 0 and 9 on the 7-segment display. Before reading further, try to do this on your own, and then compare your solution to mine, as shown in Listing 4 (file **CB-Apr23-03.txt**).

Now we remember why we initialised our global `DigitToDisplay` variable to have a value of –1. We did this to guarantee that the first time we generate a new value, that value will be different to our old (–1) value.

Count on me

The next thing I want you to do is to modify the contents of our `GetNewDigit()` function in such a way that our program repeatedly counts from 0 to 9. Once again, try to do this on your own first, and then compare your solution to the two versions I came up with, as shown in Listings 5a and 5b.

Let's start with my first version, as shown in Listing 5a (file **CB-Apr23-04.txt**). Once again, remember that, when our program starts, our global `DigitToDisplay` variable has been initialised to have a value of –1. Happily, this isn't a problem because the first thing we do is add 1 to this value, which means we will start off displaying the value 0.



```
53  // Get a new decimal digit counting 0 to 9
54  int GetNewDigit ()
55  {
56    int tmpDigit;
57
58    tmpDigit = DigitToDisplay + 1;
59    if (tmpDigit == NUM_DIGITS) tmpDigit = 0;
60
61    return tmpDigit;
62  }
```

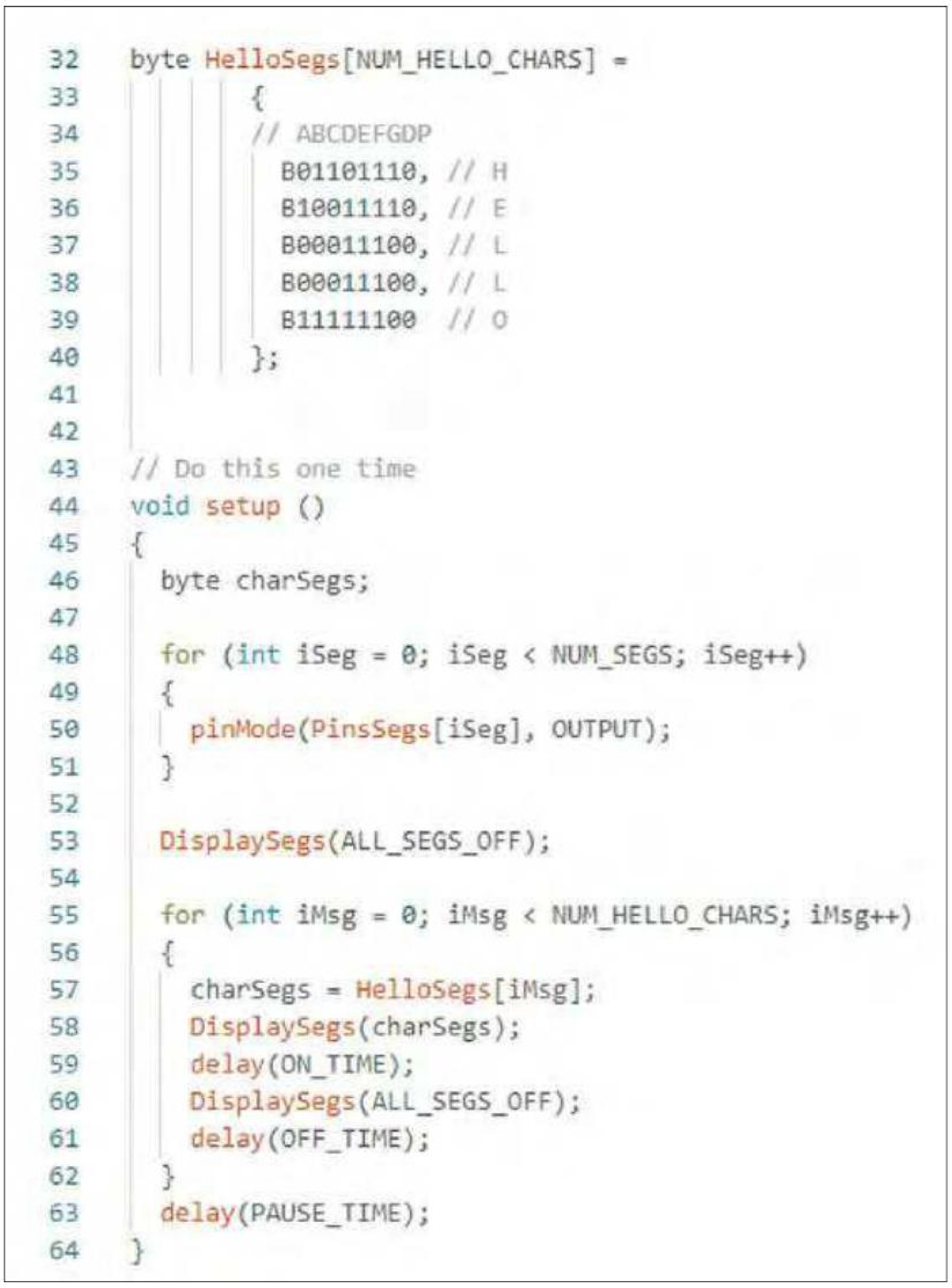
```
53  // Get a new decimal digit counting 0 to 9
54  int GetNewDigit ()
55  {
56    int tmpDigit;
57
58    tmpDigit = (DigitToDisplay + 1) % NUM_DIGITS;
59
60
61    return tmpDigit;
62  }
```

Listing 5. Two ways of counting 0 to 9: (a) (left) With test, (b) (right) With modulo operator.

The problem occurs when we reach 9. Adding 1 will give us a value of 10, which we can't replicate on our single-digit 7-segment display. We could perform a test to see if `tmpDigit == 10`. In fact, this is what we do do (if you see what I mean), except we replace the explicit 10 value with `NUM_DIGITS`, which we previously defined as being equal to 10. (We do this to future-proof our program in case we add any more digits in the future, or in *Part 5*, whichever comes first.)

If you've been paying attention, you will be squirming in your seat saying, 'You rotter!' You say this because, when talking about `if()` tests earlier, I said, 'I strongly recommend that you always use a pair of curly brackets, even if they currently embrace only a single statement,' but on Line 59 of Listing 5a I'm flouting my own rule.

The thing is, this is an unwritten rule (the best kind to apply to oneself in my experience). Always remember the adage, 'Rules are for the obedience of fools and the guidance of the wise.' In this case, breaking the rule made it easier for us to compare Listings 5a and 5b.



```
byte HelloSegs[NUM_HELLO_CHARS] =
        {
        // ABCDEFGDP
          B01101110, // H
          B10011110, // E
          B00011100, // L
          B00011100, // L
          B11111100  // O
        };


// Do this one time
void setup ()
{
  byte charSegs;

  for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
  {
    pinMode(PinsSegs[iSeg], OUTPUT);
  }

  DisplaySegs(ALL_SEGS_OFF);

  for (int iMsg = 0; iMsg < NUM_HELLO_CHARS; iMsg++)
  {
    charSegs = HelloSegs[iMsg];
    DisplaySegs(charSegs);
    delay(ON_TIME);
    DisplaySegs(ALL_SEGS_OFF);
    delay(OFF_TIME);
  }
  delay(PAUSE_TIME);
}
```

Listing 6. Adding the code to bid a cheery hello.

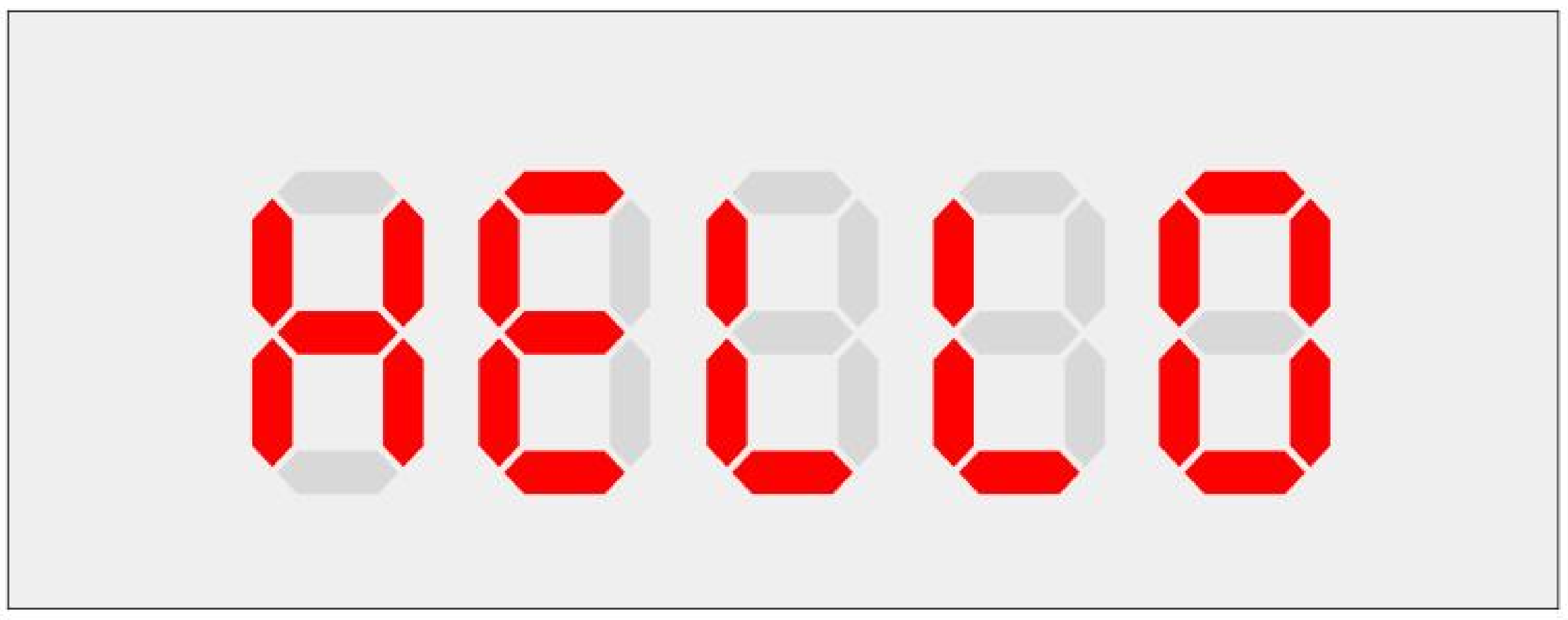


Fig.11. The segments associated with the 'HELLO' characters.

Speaking of which, I dislike having to employ tests to get around end conditions, like reaching 10 in this example. As an alternative, we can implement the solution shown in Listing 5b (file **CB-Apr23-05.txt**). In this case, after incrementing our `DigitToDisplay` value, we use the modulo % operator to divide the result by `NUM_DIGITS`, which is 10.

The modulo operator returns the remainder from an integer division. After a few moments thought, we realise that that 0 % 10 = 0, 1 % 10 = 1, 2 % 10 = 2, and so forth up to 9 % 10 = 9. However, 10 % 10 = 0, which brings us back to where we started (I feel a small 'Tra-la' is in order).

Hello there!

Do you remember when we ran the program at the beginning of this column, and it started by bidding us a cheery 'HELLO'? When you think about it, since we can control all of the segments on our display, we can use them to create characters other than the numbers 0 through 9. For example, 'H', 'E', 'L', and 'O' (Fig.11).

Just for giggles and grins, see if you can take our previous program and modify it to display the 'HELLO' message before it starts counting. As before, try to do this on your own first, and then compare your solution to mine, as shown in Listing 6 (file **CB-Apr23-06.txt**).

Note that this augments our existing code – it doesn't replace it. I started off by adding some new definitions as follows:

```
#define NUM_HELLO_CHARS 5
#define ON_TIME       1000
#define OFF_TIME       150
#define PAUSE_TIME    1000
```

As shown in Listing 6, I also declared an array called `HelloSegs[]` to define the segments I wish to use to display my message.

Next, I modified my `setup()` function to display this message. The reason for putting this code in the `setup()` function is that we wish to display the message only one time.

The question you should be asking is why we need to turn all the segments off for the `OFF_TIME` (150 milliseconds) after displaying each character. The reason is that, if we didn't do

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

this, we wouldn't be able to distinguish between the two 'L' characters.

This also explains why we add a delay of `PAUSE_TIME` (1000 milliseconds = 1 second) after displaying the final letter in our message. If we didn't do this, it would be hard to distinguish between the letter 'O' in 'HELLO' and the number 0 at the start of our count sequence.

Next time

'HELLO' is just one of the words that we can display. While we are waiting for the next exciting installment of this mega-mini-series, try to think of other characters and symbols and messages we could create (but don't cheat by looking on the internet!).

Last, but certainly not least, we still have the question we posed earlier in this column, which was 'What differentiates BCD 2421 and Excess-3 from BCD 8421.' The answer is that BCD 2421 and Excess-3 are known as 'self-complementing codes'. What does this mean? Well, in decimal, the complementary value of a number n between 0 and 9 is (9 – n). Thus, the complementary value to 0 is (9 – 0) = 9, the complementary value to 1 is (9 – 1) = 8, the complementary value to 2 is (9 – 2) = 7, and so forth.

Now, pick two complementary numbers, let's say 2 and 7. Their corresponding Excess-3 codes are 0101 and 1010, respectively. What this means is that we can generate the complement of an Excess-3 code (or a BCD 2421 code) by simply inverting all its bits, which was a very useful trick in the early days of computing. If you want to learn more about BCD, bounce over to my column *Mysteries of the Ancients: Binary Coded Decimal (BCD)* (**https://bit.ly/3wwnUsx**). Until next time – cunningly titled *Part 5* – have a good one!

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Resistors (assorted values)	**https://amzn.to/3O4RvBt**
Solderless breadboard	**https://amzn.to/3O2L3e8**
Multicore jumper wires (male-male)	**https://amzn.to/3O4hnxk**

Components (from Part 2)

7-segment display(s)	**https://amzn.to/3Afm8yu**

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

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Multi-Channel Speaker Protector – 6 channel	01101221	9.95
Multi-Channel Speaker Protector – 4 channel	01101222	7.95
Remote Control Range Extender – IR-to-UHF	15109212	5.95
Remote Control Range Extender – UHF-to-IR	15109211	7.95
AO Universal Single Op Amp Board	AO1-JAN23	7.95

DECEMBER 2022

PROJECT	CODE	PRICE
Hummingbird Amplifier	01111211	9.95
SMD Trainer PCB	29106211A	8.95
SMD Trainer PCB + parts	29106211B	13.95

NOVEMBER 2022

PROJECT	CODE	PRICE
USB Cable tester – main PCB	04108211	12.95
USB Cable tester – front panel	04108212	5.95
USB Cable tester – optional panel	SC5970	5.95
Model Railway Carriage Lights – PCB	09109211	6.95
AO transfmr PCB – standard VTX-A range	VTX-101-007	6.95
AO transfmr PCB – dual-outline VTX102-3001/101-3002	VTX-Dual	6.95

OCTOBER 2022

PROJECT	CODE	PRICE
SMD Test Tweezers – PCB and pair of tweezer arms	04106211-2	11.95
SMD Test Tweezers – programmed PIC12F1572-I/SN	0410621A	7.95
Tele-com	12110211	12.95

SEPTEMBER 2022

PROJECT	CODE	PRICE
Touchscreen Digital Preamp – main board	01103191	12.95
Touchscreen Digital Preamp – adaptor board pair	01103192	5.95
20A DC Motor Speed Controller	11006211	9.95

AUGUST 2022

PROJECT	CODE	PRICE
Multi-purpose Battery Manager – I/O Expander module	11104212	5.95
Multi-purpose Battery Manager – Switch Module	11104211	8.95
Simple MIDI Music Keyboard (for 8 switches)	23101213	6.95
Nano Pong	08105212	7.95

JULY 2022

PROJECT	CODE	PRICE
Silicon Labs AM/FM/SW Radio	CSE210301C	10.95
Level Crossing Controller	09108211	6.95

JUNE 2022

PROJECT	CODE	PRICE
Full-wave Motor Speed Controller	1010221	8.95
PIC Programming Helper for 8-pin PICs only	24106211	7.95
PIC Programming Helper for 8, 14 or 20-pin PICs	24106212	10.95
Advanced GPS Computer	05102211	9.95

MAY 2022

PROJECT	CODE	PRICE
Bus board PCB for Analogue Vocoder	AO1-MAY22	10.95
Complete set of 14 PCBs for Analogue Vocoder	AO2-MAY22	97.95
Programmed EEPROM for Digital FX Unit	FX1-MAY22	10.95
Programmed PIC for Digital FX Unit using potentiometer	FX2-MAY22	8.95

APRIL 2022

PROJECT	CODE	PRICE
64-key MIDI Matrix shield	23101211	8.95
64-key MIDI Matrix switch board	23101212	11.95
High-current Battery Balancer	14102211	10.95
Digital FX Unit – using potentiometer	01102211	9.95
Digital FX Unit – using BCD switch	01102212	9.95
Universal Audio PSU	AO1-APR22	11.95

MARCH 2022

PROJECT	CODE	PRICE
Mini Isolated Serial Link	24102211	£5.95
Busy Loo Indicator	16112201	£5.95
Analogue Vocoder – Band-pass filter board	AO1-MAR22	9.95
Analogue Vocoder – HP/LP filter board	AO2-MAR22	9.95

FEBRUARY 2022

PROJECT	CODE	PRICE
Arduino-based Power Supply	18106201	9.95
Battery Monitor Logger	11106201	10.95
Electronic Wind Chimes	23011201	10.95
Analogue Vocoder – Driver Amplifier	AO-FEB22	8.95

JANUARY 2022

PROJECT	CODE	PRICE
Vintage battery Radio Li-ion Power Supply	11111201	9.95
MiniHeart: A Miniature Heartbeat Simulator	01109201	8.95

DECEMBER 2021

PROJECT	CODE	PRICE
AM/FM/SW Digital Receiver	CSE200902A	13.95
Balanced Input and Attenuator for USB CODEC	01106202	11.95

NOVEMBER 2021

PROJECT	CODE	PRICE
Dual Battery Lifesaver	11111202	£6.95

OCTOBER 2021

PROJECT	CODE	PRICE
Mini Wi-Fi LCD BackPack	24106201	£8.95

SEPTEMBER 2021

PROJECT	CODE	PRICE
USB SuperCodec PCB	01106201	£14.95
Audio DDS Oscillator PCB	01110201	£5.95
Audio DDS Oscillator rotary encoder	01110201-ENC	6.95
Programming Adaptor Board for Audio DDS Oscillator	01110202	£5.95
High-power Ultrasonic Cleaner main PCB	04105201	£14.95
High-power Ultrasonic Cleaner front-panel PCB	04105202	
Night Keeper Lighthouse PCB	08110201	£5.95

AUGUST 2021

PROJECT	CODE	PRICE
Ol' Timer PCB	19104201	£11.95
Ol' Timer 8x8 RGB LED module using WS2812B	19104201-88	£8.95
Ol' Timer set of acrylic case pieces and spacer	19104201-ACR	£8.75
Ol' Timer DS3231 RTC IC wide SOIC-16	19104201-RTC	£5.95
Wideband Digital RF Power Meter	04106201	£9.75
Switchmode 78xx regulators ***(PACK of 5!)***	18105201	£7.95
Cool Beans SMAD display	CB-AUG21	£11.95

JULY 2021

PROJECT	CODE	PRICE
ATtiny816 Breakout / Dev Board with Capacitive Touch	24110181	£9.75
IR Remote Control Assistant (Jaycar version)	15005201	£8.95
IR Remote Control Assistant (Altronics version)	15005202	£8.95
PIC18F Development Board	PNM-JUL21	£12.95
Microphone Preamplifier	AO-JUL21	£11.95

PCBs for most recent *PE*/*EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

Double-sided | plated-through holes | solder mask

PROJECT	CODE	PRICE
JUNE 2021		
Roadies' Test Signal Generator (surface-mount version)	01005201	£8.95
Roadies' Test Signal Generator (through-hole version)	01005202	£9.95
Touchscreen Wide-range RCL Box (Resistor module)	04104201	£18.95
Touchscreen Wide-range RCL Box (Ind/Cap module)	04104202	
KickStart Part 3 – Gyrator-based Audio Filter	KS3-2021	£7.95
MAY 2021		
7-Band Equaliser (Mono)	01104201	£8.95
7-Band Equaliser (Stereo)	01104202	£10.95
Car Altimeter	05105201	£7.95
APRIL 2021		
Reflow Oven – DSP Active Crossover (CPU)	01106193	£19.95
Reflow Oven – DSP Active Crossover (Front panel)	01106195	
Reflow Oven – DSP Active Crossover (LCD)	01106196	
Frequency Reference Signal Distributor	CSE200103	£8.95
MARCH 2021		
Nutube Guitar Effects Pedal	01102201	£12.95
Programmable Thermal Regulator (Peltier Interface)	21109181	£18.95
Programmable Thermal Regulator (Peltier Driver)	21109182	
Tunable HF Preamp	CSE190502	£8.95
FEBRUARY 2021		
4G Remote Monitoring	27111191	£9.95
JANUARY 2021		
Nutube Valve Preamplifier	01112191	£12.95
Arduino DCC Controller	09207181	£10.95
DECEMBER 2020		
Pseudo-Random Sequence Generator	16106191	£7.95
Clever Charger	14107191	£11.95
PE Theremin Amplifier	AO-1220-01	£8.95
NOVEMBER 2020		
LED Christmas Tree (1 off)	16107181-1	£6.95
LED Christmas Tree (4 off)	16107181-2	£14.95
LED Christmas Tree (12 off)	16107181-3	£24.95
LED Christmas Tree (20 off)	16107181-4	£34.95
USB/SPI Interface Board	16107182	£5.95
45V/8A Power Supply PCB *plus* acrylic spacer	18111181	£14.95
45V/8A Power Supply front panel five-way display bezel	18111181-BZ	£3.95
Five-way LCD Panel Meter/Display	18111182	£7.95
OCTOBER 2020		
Digital Audio Millivoltmeter	04108191	£9.95
Precision Signal Amplifier	04107191	£7.95
SEPTEMBER 2020		
PE Theremin PSU	AO-0920-01	£5.95
PE Theremin PSU transformer	AO-0920-02	£7.95
Micromite Explore-28	07108191	£6.95
Ultrabrite LED Driver	16109191	£6.95
AUGUST 2020		
Micromite LCD BackPack V3	07106191	£9.95
Steering Wheel Audio Button to Infrared Adaptor	05105191	£7.95
JULY 2020		
AM/FM/CW Scanning HF/VHF RF Signal Generator	04106191	£13.95
Speech Synthesiser with the Raspberry Pi Zero	01106191	£5.95
PE Mini-organ PCB	AO-0720-01	£14.95
PE Mini-organ selected parts	AO-0720-02	£8.95
High-current Solid-state 12V Battery Isolator – control	05106191	£6.95
High-current Solid-state 12V Battery Isolator FET (2oz)	05106192	£9.95

PROJECT	CODE	PRICE
JUNE 2020		
Arduino breakout board – 3.5-inch LCD Display	24111181	£6.95
Six-input Audio Selector main board	01110191	£10.95
Six-input Audio Selector switch panel board	01110192	
MAY 2020		
Ultra-low-distortion Preamplifier Input Selector	01111112	£11.25
Ultra-low-distortion Preamplifier pushbutton Input Selector	01111113	
Universal Regulator	18103111	£7.95
433MHz Wireless Data Repeater	15004191	£8.50
Bridge-mode Adaptor for Amplifier	01105191	£7.95
iCEstick VGA Terminal	02103191	£5.95
Analogue noise with tilt control	AO-0520-01	£7.95
Audio Spectrum Analyser	PM-0520-01	£8.95
APRIL 2020		
Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
Diode Curve Plotter	04112181	£10.95
Steam Train Whistle / Diesel Horn Sound Generator	09106181	£8.50
Universal Passive Crossover (one off)	UPC0320	£12.50

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Motion-Sensing 12V Power Switch	05102191	£5.95
USB Keyboard / Mouse Adaptor	24311181	£8.50
DSP Active Crossover (ADC)	01106191	£29.95
DSP Active Crossover (DAC) ×2	01106192	
DSP Active Crossover (CPU)	01106193	
DSP Active Crossover (Power/routing)	01106194	
DSP Active Crossover (Front panel)	01106195	
DSP Active Crossover (LCD)	01106196	
JANUARY 2020		
Isolated Serial Link	24107181	£8.50
DECEMBER 2019		
Extremely Sensitive Magnetometer	04101011	£16.75
Four-channel High-current DC Fan and Pump Controller	05108181	£8.75
Useless Box	08111181	£11.50
NOVEMBER 2019		
Tinnitus & Insomnia Killer (Jaycar case – see text)	01110181	£9.95
Tinnitus & Insomnia Killer (Altronics case – see text)	01110182	£9.95
OCTOBER 2019		
Programmable GPS-synced Frequency Reference	04107181	£11.50
Digital Command Control Programmer for Decoders	09107181	£9.95
Opto-isolated Mains Relay (main board)	10107181	£11.50
Opto-isolated Mains Relay (2 × terminal extension board)	10107182	
AUGUST 2019		
Brainwave Monitor	25108181	£12.90
Super Digital Sound Effects Module	01107181	£6.95
Watchdog Alarm	03107181	£8.00
PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
PE Theremin component pack (see p.56, August 2019)	PETY0819	£15.00
JULY 2019		
Full-wave 10A Universal Motor Speed Controller	10102181	£12.90
Recurring Event Reminder	19107181	£8.00
Temperature Switch Mk2	05105181	£10.45
JUNE 2019		
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USB Flexitimer	19106181	£10.45
MAY 2019		
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Deluxe Frequency Switch	05104181	£10.45
USB Port Protector	07105181	£5.95
APRIL 2019		
Heater Controller	10104181	£14.00
MARCH 2019		
10-LED Bargraph Main Board	04101181	£11.25
+Processing Board	04101182	£8.60
FEBRUARY 2019		
1.5kW Induction Motor Speed Controller	10105122	£24.95
NOVEMBER 2018		
Super-7 AM Radio Receiver	06111171	£15.95
OCTOBER 2018		
6GHz+ Touchscreen Frequency Counter	04110171	£12.95
Two 230VAC MainsTimers	10108161 10108162	£11.95

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SEPTEMBER 2018		
3-Way Active Crossover	01108171	£17.95
Ultra-low-voltage Mini LED Flasher	16110161	£5.95
AUGUST 2018		
Universal Temperature Alarm	03105161	£7.95
Power Supply For Battery-Operated Valve Radios	18108171 18108172 18108173 18108174	£24.95
JULY 2018		
Touchscreen Appliance Energy Meter – Part 1	04116061	£14.95
Automotive Sensor Modifier	05111161	£12.95
JUNE 2018		
High Performance 10-Octave Stereo Graphic Equaliser	01105171	£14.95
MAY 2018		
High Performance RF Prescaler	04112162	£10.45
Micromite BackPack V2	07104171	£8.45
Microbridge	24104171	£5.95
APRIL 2018		
Spring Reverberation Unit	01104171	£13.95
DDS Sig Gen Lid	Black	£5.95
DDS Sig Gen Lid	Blue	£5.95
DDS Sig Gen Lid	Clear	£5.95
MARCH 2018		
Stationmaster Main Board	09103171	£17.75
+ Controller Board	09103172	
SC200 Amplifier Module – Power Supply	01109111	£16.45
FEBRUARY 2018		
GPS-Synchronised Analogue Clock Driver	04202171	£11.95
High-Power DC Motor Speed Controller – Part 2		
+ Control Board	11112161	£11.95
+ Power Board	11112162	£15.30
JANUARY 2018		
High-Power DC Motor Speed Controller – Part 1	11112161	£15.30
Build the SC200 Amplifier Module	01108161	£13.95
DECEMBER 2017		
Precision Voltage and Current Reference – Part 2	04110161	£14.95
NOVEMBER 2017		
50A Battery Charger Controller	11111161	£12.95
Micropower LED Flasher (45 × 47mm)	16109161	£7.95
(36 × 13mm)	16109162	£5.95
Phono Input Converter	01111161	£7.95
SEPTEMBER 2017		
Compact 8-Digit Frequency Meter	04105161	£12.95
AUGUST 2017		
Micromite-Based Touch-screen Boat Computer GPS	07102122	£10.45
Fridge/Freezer Alarm	03104161	£7.95
JULY 2017		
Micromite-Based Super Clock	07102122	£10.45
Brownout Protector for Induction Motors	10107161	£12.90
JUNE 2017		
Ultrasonic Garage Parking Assistant	07102122	£10.45
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Next Month – in the May issue

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This signal generator provides very high calibrated accuracy with an error of just ten parts in a billion, which translates to 0.1Hz at 10MHz. It also has plenty of features, including amplitude and frequency modulation.

500W Power Amplifier – Part 2

We've described our mighty new 500W Amplifier, and we follow on next month with the amplifier construction, beginning with the PCB (Amplifier Module) assembly.

Improved SMD Test Tweezers

Our SMD Test Tweezers project from the October 2022 issue has been extremely popular. They are handy, compact, easy to use, easy to build and inexpensive. So, we decided to see what features we could add simply by upgrading the microcontroller at its heart.

R HAND
SILICON CHIP SMD TEST TWEEZER ARM

CJMCU-7620 Gesture Recognition Module

With this module, you can experiment with sensing and recognising gestures made with your hands. It is very small, relatively low in cost and can easily be hooked up to an Arduino or a Micromite.

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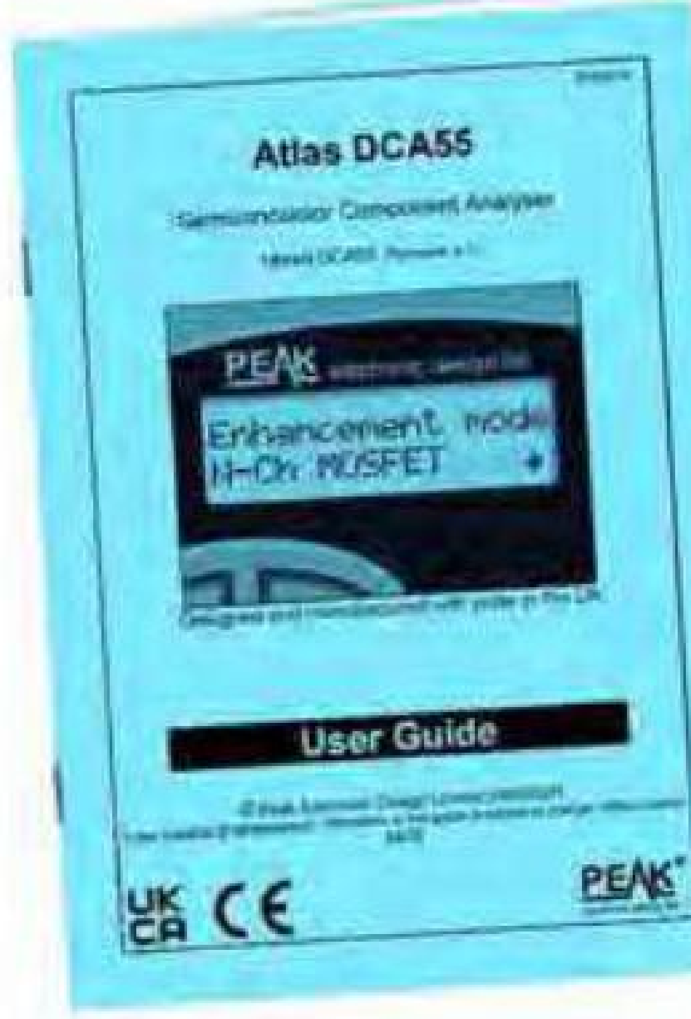

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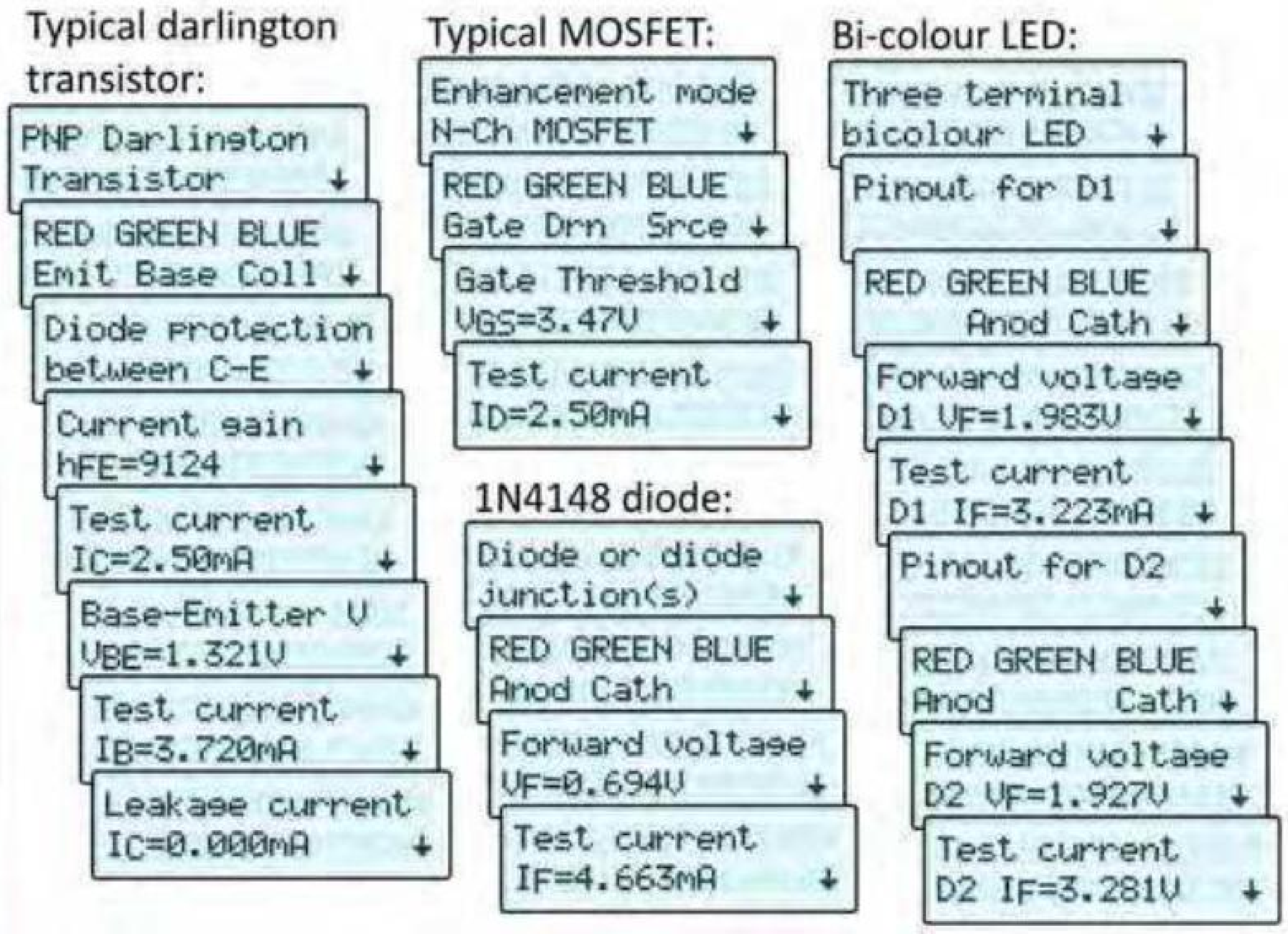
- **Auto and manual power-off.**

Example Screenshots



Typical darlington transistor:

```
PNP Darlington
Transistor     ↓
RED GREEN BLUE
Emit Base Coll ↓
Diode protection
between C-E    ↓
Current gain
hFE=9124       ↓
Test current
IC=2.50mA      ↓
Base-Emitter V
VBE=1.321V     ↓
Test current
IB=3.720mA     ↓
Leakage current
IC=0.000mA     ↓
```

Typical MOSFET:

```
Enhancement mode
N-Ch MOSFET    ↓
RED GREEN BLUE
Gate Drn  Srce ↓
Gate Threshold
VGS=3.47V      ↓
Test current
ID=2.50mA      ↓
```

1N4148 diode:

```
Diode or diode
junction(s)    ↓
RED GREEN BLUE
Anod Cath      ↓
Forward voltage
VF=0.694V      ↓
Test current
IF=4.663mA     ↓
```

Bi-colour LED:

```
Three terminal
bicolour LED   ↓
Pinout for D1
               ↓
RED GREEN BLUE
     Anod Cath ↓
Forward voltage
D1 VF=1.983V   ↓
Test current
D1 IF=3.223mA  ↓
Pinout for D2
               ↓
RED GREEN BLUE
Anod      Cath ↓
Forward voltage
D2 VF=1.927V   ↓
Test current
D2 IF=3.281V   ↓
```

UK tracked and insured postage is £6.66. Airmail outside of UK calculated at checkout, typically £11.52 for Europe.

It's only possible to show summary specifications here. Please ask if you'd like detailed data. Further information is also available on our website. Product price refunded if you're not happy.

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